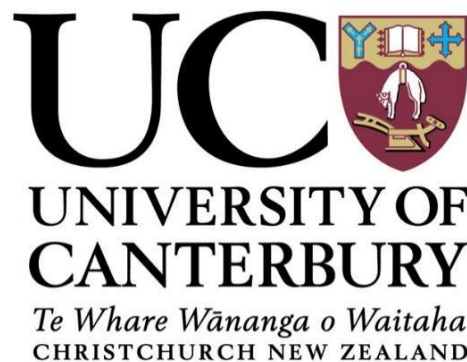


Impact assessment of a far-field tsunami scenario for building damage and habitability in Christchurch, New Zealand

A thesis
submitted in partial fulfilment of the requirements
for the degree of
Master of Science in Hazard and Disaster Management
at the
University of Canterbury
by
Finn Scheele



Department of Geological Sciences

University of Canterbury

2016

Abstract

Tsunami are powerful natural events which become hazardous if coastal communities are exposed to the effects. The potential impacts include damage to buildings, infrastructure, human casualties, and displacement of residents. The Canterbury coastline is exposed to far-field tsunamis originating from locations distant to New Zealand. Understanding the potential impacts of a major tsunami to a coastal region enables better planning and preparedness initiatives to take place. Although inundation modelling of a major far-field tsunami affecting Christchurch was available, a detailed impact assessment had not been undertaken previously.

The objectives of this thesis are to assess the post-arrival impacts of specific far-field tsunami scenarios on Christchurch communities, focusing on damage to buildings, habitability of residential dwellings and the displacement of residents within the first week following the tsunami arrival. The research contributes to the RiskScape programme, and provides resources for emergency management planning and scenario exercising. The risk assessment framework is used in this thesis as a conceptual basis for tsunami impact assessment.

A literature review of the tsunami hazard to Christchurch, tsunami impacts, impact assessment methodologies, and factors contributing to residential habitability and human displacement was conducted. The impact assessment process for estimating building damage related the inundation modelling with an asset database of exposed buildings, and used fragility functions to assess the probability of reaching certain damage states. The building asset database was created using GIS and field surveying data of building attributes. The residential habitability and human displacement was assessed spatially and temporally for the first week following the tsunami wave arrival. The literature review and interviews were used to inform the relative influence of factors contributing to habitability and displacement. Modelling using GIS was performed to assess the habitability and displacement within the inundation zone by considering the factors of building damage, access, and functionality of utilities (electricity, water, and wastewater).

For the primary scenario modelled, approximately 950 buildings are collapsed or washed away, 2,150 suffer moderate to complete damage, and 1,600 experience minor or no damage. On the first day of the tsunami wave arrival, approximately 5,000 residential dwellings are uninhabitable 11,000 residents displaced, representing all housing and population within the inundation zone. At one week after the event, there are approximately 2,850 uninhabitable residences and 6,250 people still displaced.

The results of this project may be used for enhanced emergency management planning and scenario exercising. The methodologies developed may be applied to other scenarios, locations, and different natural hazards.

Acknowledgements

I would firstly like to thank my supervision team: Thomas Wilson, Tim Davies, Emily Lane, and Matthew Hughes. You've all shown great support and relentless enthusiasm for the project, and the contributions of a team with such diverse experience and perspectives has been extremely valuable.

Thank you to James Thompson (Canterbury CDEM) and Marion Gadsby (ECan) for all of your ideas, enthusiasm, and the opportunity for a project that makes a practical contribution to emergency management. The funding support for the project was much appreciated!

Thank you to all of the people in the RiskScape team (GNS and NIWA). Kate Crowley, for the great ideas relating to habitability, Nick Horspool and Ryan Paulik for all of the help with fragility functions, Sheng-Lin Lin for help with RiACT, and Shaun Williams for the great advice and interest in the impact modelling.

Thank you to Caitlin Goodall (CCC) for generously helping with provision of data. Thank you to Karn Snyder-Bishop for the great assistance with infrastructure disruption post-event. Thank you to the interviewees who generously gave their time, and everyone else not mentioned here who all contributed to the project with advice and interest.

A big thank you to all of the extremely helpful people within the Geology department.

To James Williams and Lina Le: Thank you for being awesome Tsunami Masters buddies! Always having people who understand the project for valuable discussions, support and fun times was fantastic.

To all my awesome friends, thank you for a fantastic year! You're all part of what makes life great. Special thanks to Claire for being amazing, especially during the final months of the thesis!

And lastly, thank you to my parents, your relentless support and good company has been essential.

Contents

Abstract.....	i
Acknowledgements	iii
List of Figures	vii
List of Tables	x
Chapter 1: Introduction.....	1
1.1 Context of study.....	1
1.2 Aims and objectives.....	2
1.3 Risk management framework.....	2
1.4 Research methodology and thesis structure	6
1.5 Literature Review	7
1.5.1 Tsunami in New Zealand	7
1.5.2 Tsunami in Canterbury	10
1.5.3 Inundation modelling and scenarios	11
1.5.4 Tsunami impacts.....	15
Chapter 2: Assessment of building damage.....	17
2.1 Introduction.....	17
2.2 Literature review.....	18
2.2.1 Impact and Vulnerability Assessments	18
2.2.2 Fragility and damage functions	23
2.2.2.1 Function development	23
2.2.2.2 Applications.....	27
2.2.2.3 Limitations.....	29
2.2.2.4 Application to Christchurch context.....	30
2.2.3 RiskScape	33
2.2.3.1 Using RiskScape for tsunami impact assessment	34
2.2.3.2 Using RiskScape to model tsunami impacts in Christchurch	34
2.3 Methodology.....	35
2.3.1 Overview.....	35
2.3.2 Impact assessment process.....	36
2.3.3 Creating a database of building assets.....	37

2.3.3.1	Overview	37
2.3.3.2	The RiskScape building asset database	38
2.3.3.3	Trial field survey of Sumner buildings	38
2.3.3.4	Identified problems with RiskScape database	39
2.3.3.5	Field survey of buildings	41
2.3.3.6	GIS methods for creating the asset database	45
2.3.3.7	Post-processing of building footprints	46
2.3.3.8	Merging of data	47
2.3.3.9	Extrapolation	47
2.3.3.10	Residential population calculation	48
2.3.3.11	Comparison of asset databases	49
2.3.4	Impact modelling	50
2.4	Results	55
2.4.1	Number of buildings per damage state and comparison of scenarios	55
2.4.2	Probability of damage state	61
2.4.3	Population	64
2.4.4	Impacts by building purpose	64
2.4.5	Comparison of database versions	67
2.5	Discussion	69
2.5.1	The impact on communities	69
2.5.2	Field surveying with the RiACT application	69
2.5.3	Different methods of displaying data	71
2.5.4	Uncertainties and limitations of impact assessment modelling	72
2.5.4.1	Inundation modelling	72
2.5.4.2	Asset database	73
2.5.4.3	Fragility functions	73
2.5.4.4	Other factors	74
2.5.5	RiskScape software	74
2.5.6	Summary	75
Chapter 3:	Assessment of building habitability and human displacement	76
3.1	Introduction	76
3.2	Literature review	77

3.2.1	Factors influencing building habitability and human displacement	77
3.2.1.1	Direct factors	78
3.2.1.2	Indirect and intangible factors	79
3.2.1.3	Population movement	80
3.2.2	Modelling human displacement	81
3.2.3	Interviews	83
3.2.4	Summary	84
3.3	Methodology	85
3.3.1	Overview	85
3.3.2	Building and population data	87
3.3.3	Access and functionality of utilities	87
3.3.4	Assessment in GIS	89
3.4	Results	91
3.5	Discussion	97
3.5.1	Discussion of results	98
3.5.2	Uncertainty and limitations	98
3.5.3	Other factors	99
3.5.4	Potential future research	101
3.5.5	Summary	102
Chapter 4:	Conclusions and recommendations	103
4.1	Conclusions	103
4.1.1	Assessment of building damage	103
4.1.2	Assessment of building habitability and human displacement	104
4.1.3	Summary	105
4.2	Recommendations and research directions	106
4.2.1	Recommendations	106
4.2.2	Research directions	107
References	109
Appendix A:	Inundation modelling scenario maps	118
Appendix B:	Distribution of building damage states in Redcliffs	121
Appendix C:	Polygons of access and utility disruption	123
Appendix D:	Interview questions and Human Ethics approval	135

List of Figures

Figure 1.1: Risk management framework (adapted from <i>Standards New Zealand, 2009</i>)..	3
Figure 1.2: Impact assessment process. The hazard (e.g. inundation modelling) and exposure (e.g. building asset database) modules are related by considering the vulnerability of exposed assets to the hazard (e.g. using fragility functions), to produce outputs of the potential impacts.....	5
Figure 1.3: Source locations of regional and distant tsunami to have affected New Zealand historically (black dots), and subduction zones which may be future tsunami sources (black lines with labels). Adapted from data obtained from the New Zealand Tsunami Database (<i>GNS Science, 2014</i>).	8
Figure 1.4: Source locations of locally generated tsunami during historical times (black dots), and the tectonic plate interface between the Australian and Pacific plates. Source locations include tsunami generated within inland bodies of water. Adapted from data obtained from the New Zealand Tsunami Database (<i>GNS Science, 2014</i>).....	10
Figure 1.5: Inundation modelling of the Okada40 scenario for Christchurch, showing the inundation depths.....	14
Figure 2.1: Example of loss curve from probabilistic modelling, for direct property loss in Auckland due to tsunami (from (<i>Horspool et al., 2015</i>)).....	21
Figure 2.2: Tsunami water depth and Relative Vulnerability Index applied to buildings in Manly, Sydney, based on the PVTa-3 model (from <i>Dall’Osso et al. 2009</i>).....	22
Figure 2.3: Example of a fragility function for reinforced concrete structures, showing six different damage states (from <i>Suppasri et al. 2013a</i>).....	24
Figure 2.4: Example of a damage function, for different construction types (from <i>Reese et al. 2007</i>).	25
Figure 2.5: The RiskScape process (from <i>GNS Science/NIWA, 2014</i>).....	33
Figure 2.6: Overview of the building damage impact assessment methodology.	35
Figure 2.7: Impact assessment process (left), and the specific impact assessment process for tsunami damage to buildings (right).	36
Figure 2.8: Overview of the process for creating the asset database of buildings.....	37

Figure 2.9: Sumner trial building survey area, showing the use category of buildings surveyed.	39
Figure 2.10: Areas and transects traversed for field survey of buildings. All buildings within the commercial areas that did not already have data available were surveyed.	42
Figure 2.11: The RiACT application interface (from <i>Lin et al., 2014</i>).	43
Figure 2.12: The main GIS process used during the creation of the asset database.	46
Figure 2.13: Outline of the process used for impact modelling and producing results from the outputs.	53
Figure 2.14: Map showing the proportion of buildings grouped into damage states for suburbs within the inundation zone (clipped to the Okada40 scenario, and coloured for differentiation). The total number of buildings within the suburbs is in parentheses. Some suburbs with very few buildings impacted (e.g. Mt Pleasant, Bexley) are not shown on this map.	58
Figure 2.15: Example map of Redcliffs showing the damage state distribution of a single run of the impact assessment modelling for the Okada40 scenario.	60
Figure 2.16: Map of Sumner showing the probability of each building reaching or exceeding DS3 (major damage), for the Okada40 scenario.	62
Figure 2.17: Map of Sumner showing the probability of each building reaching or exceeding DS5 (collapse), for the Okada40 scenario.	63
Figure 3.1: Overview of the methodology for assessing building habitability and the displacement of residents following a tsunami event. For each step of the process, the information sources and main assumptions are listed. The red boxes in the “Assumptions” column indicate the relatively high degree of uncertainty involved with those steps in the process.	86
Figure 3.2: Maps showing the proportion of displaced residents per suburb, for different days following the tsunami event (Okada40). The suburbs are clipped to the inundation limit.	94
Figure 3.3: Number of residents displaced for between 1 – 7 days per meshblock (excluding those residents displaced for longer), based on the Okada40 scenario.	95
Figure 3.4: Number of residents displaced for at least one week per meshblock, based on the Okada40 scenario.	96

Figure A.1: Inundation modelling of the Okada25A scenario for Christchurch, showing the inundation depths.	118
Figure A.2: Inundation modelling of the Okada25B scenario for Christchurch, showing the inundation depths.	119
Figure A.3: Inundation modelling of the Okada30 scenario for Christchurch, showing the inundation depths.	120
Figure B.1: Example map of Redcliffs showing the damage state distribution of a single run (#2) of the impact assessment modelling for the Okada40 scenario.	121
Figure B.2: Example map of Redcliffs showing the damage state distribution of a single run (#3) of the impact assessment modelling for the Okada40 scenario.	122
Figure C.1: Polygon showing area of no access for Day 1 following the tsunami wave arrival (Okada40).	124
Figure C.2: Polygon showing area of no access for Days 2 - 3 following the tsunami wave arrival (Okada40).	125
Figure C.3: Polygon showing area of no access for Day 4 following the tsunami wave arrival (Okada40).	126
Figure C.4: Polygon showing area of no power for Days 1 - 4 following the tsunami wave arrival (Okada40).	127
Figure C.5: Polygon showing area of no power for Days 5 – 6 following the tsunami wave arrival (Okada40).	128
Figure C.6: Polygon showing area of no power for Day 7 onwards following the tsunami wave arrival (Okada40).	129
Figure C.7: Polygon showing area of no water for Days 1 - 4 following the tsunami wave arrival (Okada40).	130
Figure C.8: Polygon showing area of no water for Day 5 onwards following the tsunami wave arrival (Okada40).	131
Figure C.9: Polygon showing area of no wastewater for Days 1 - 2 following the tsunami wave arrival (Okada40).	132
Figure C.10: Polygon showing area of no wastewater for Days 3 – 5 following the tsunami wave arrival (Okada40).	133
Figure C.11: Polygon showing area of no wastewater for Day 6 onwards following the tsunami wave arrival (Okada40).	134

List of Tables

Table 2.1: The pros and cons of different approaches for impact assessments (adapted from <i>Power, 2013</i>).....	19
Table 2.2: Summary of fragility and damage functions	31
Table 2.3: Comparison of statistics for the RiskScape building database and trial field survey of Sumner.....	40
Table 2.4: Data sources used for creating the building asset database.....	45
Table 2.5: Summary of the number of buildings for each source of attribute data within the database.	48
Table 2.6: Summary of number of buildings per construction type, for the new database and RiskScape database.	49
Table 2.7: Summary of number of buildings per use category, for the new database and RiskScape database.....	50
Table 2.8: Damage state classification and description used for impact modelling. Table adapted from <i>Suppasri et al. (2013)</i>	52
Table 2.9: Number of buildings per damage state for each scenario.	56
Table 2.10: The number of buildings per use category within the inundation zone of each scenario.	57
Table 2.11: The percentage of buildings (all use categories) per damage state, separated by suburb (based on the mean of 100 impact model runs).	59
Table 2.12: Number of residences and population within the inundation zone for the Okada40 scenario.	64
Table 2.13: The percentage of residential buildings per damage state, separated by suburb (based on the mean of 100 impact model runs).....	66
Table 2.14: The impact on commercial buildings within the inundation zone, displayed as percentage of buildings per damage state (based on the mean of 100 impact model runs). The four main commercial zones are separated out.....	66
Table 2.15: The impact on schools within the inundation zone, displayed as the percentage of buildings per damage state (based on the mean of 100 impact model runs).	67

Table 2.16: Comparison of number of buildings per damage state for three different extrapolated versions of the asset database (Ex. 1 – 3), as well as the RiskScape asset database.....	68
Table 3.1: The main factors identified as contributing to whether a building is determined as habitable, and whether residents are willing to return. Sources: <i>Comerio (1997); Jha and Dwyne (2010); Peacock et al. (2007); Power (2013); Wright et al. (2012)</i>	77
Table 3.2: Factors considered in the GIS analysis of building habitability, and the weightings applied. A score is applied for access, power, water and wastewater if they are unavailable for a building.	90
Table 3.3: Number of habitable or uninhabitable residences per suburb, for the first 7 days following the tsunami event.	92
Table 3.4: Number of displaced residents per suburb, for the first 7 days following the tsunami event. The number of residents is based on the average number of occupants per household within the inundation zone (2.18, see page 48 for calculation), rounded to the nearest whole number.....	93
Table 3.5: Sensitivity test of using 5 different runs of the impact assessment model for building damage, as part of the habitability assessment, showing the total number of uninhabitable residences per day.	97

Chapter 1: Introduction

1.1 Context of study

Tsunami are powerful natural events which become hazardous if coastal communities are exposed to their effects. The impacts are potentially devastating, as evidenced by the 2004 Indian Ocean and 2011 Great East Japan tsunami events, which resulted in great loss of life and extensive damage to buildings and infrastructure (Fraser et al., 2013; Ghobarah et al., 2006; Norio et al., 2011; Rodriguez et al., 2006). The direct impacts such as casualties and building damage are caused primarily by tsunami inundation, currents and mobilised debris (Bryant, 2008; Power, 2013a). Additionally, indirect impacts to society can be equally severe and include human displacement, economic loss, psychosocial impacts, and disruption to services. Tsunami impacts are influenced by local geography and topography, as well as the vulnerability of exposed assets and populations (Power, 2013a; Suppasri et al., 2013b).

Understanding the potential impacts of a major tsunami on a coastal region enables better planning and preparedness initiatives to take place. The Canterbury coastline is exposed to far-field tsunamis (i.e. originating from locations distant from New Zealand: NZIER, 2015; Power, 2013a). Significant populations, buildings, infrastructure and lifelines are vulnerable to the effects of tsunami inundation. Although tsunamis have affected the region several times during the period of European settlement, the impacts have generally been minor due to relatively sparse population and limited asset exposure compared to present levels of coastal development (GNS Science, 2014). Potential tsunami inundation from a far-field source has been modelled (Lane et al., 2014, 2012), however a detailed impact assessment has not been undertaken previously.

Of particular interest to Canterbury Civil Defence and Emergency Management (CDEM) are the potential impacts on Christchurch buildings, on the habitability of residences post-event, and the displacement of populations. Estimating these impacts will better inform planning and scenario exercising. The focus of this study is to examine the impacts of tsunami on buildings and to forecast habitability of affected areas for the first week

following the tsunami arrival, as this is a critical time period for emergency management response. Additionally, this study aims to contribute to the risk modelling tool “RiskScape”, developed jointly by GNS Science and the National Institute of Water and Atmospheric Research (NIWA).

1.2 Aims and objectives

The aims and objectives of this thesis are as follows:

- Use existing tsunami hazard modelling data to assess the post-arrival impacts of specific far-field tsunami scenarios on Christchurch communities, focusing on damage to buildings, habitability of residential dwellings and the displacement of residents within the first week following the tsunami arrival.
- Use and contribute to the improvement of the risk modelling tool "RiskScape", including updating building asset databases and investigating the use of fragility functions to assess building damage.
- Develop detailed impact assessment scenario resources for Canterbury CDEM Group, for use during exercising and planning.

1.3 Risk management framework

The risk management framework is a standardised process for reducing risk (Standards New Zealand, 2009). The three components of risk assessment are risk identification, risk analysis, and risk evaluation (Figure 1.1). The risk management approach has been used extensively for assessing tsunami risk globally (e.g. Dominey-Howes and Goff, 2013; Jelínek et al., 2012; Papadopoulos and Dermentzopoulos, 1998), and is commonly used by organisations in New Zealand (Standards New Zealand, 2009). The risk assessment framework is used in this thesis as a conceptual basis for tsunami impact assessment.

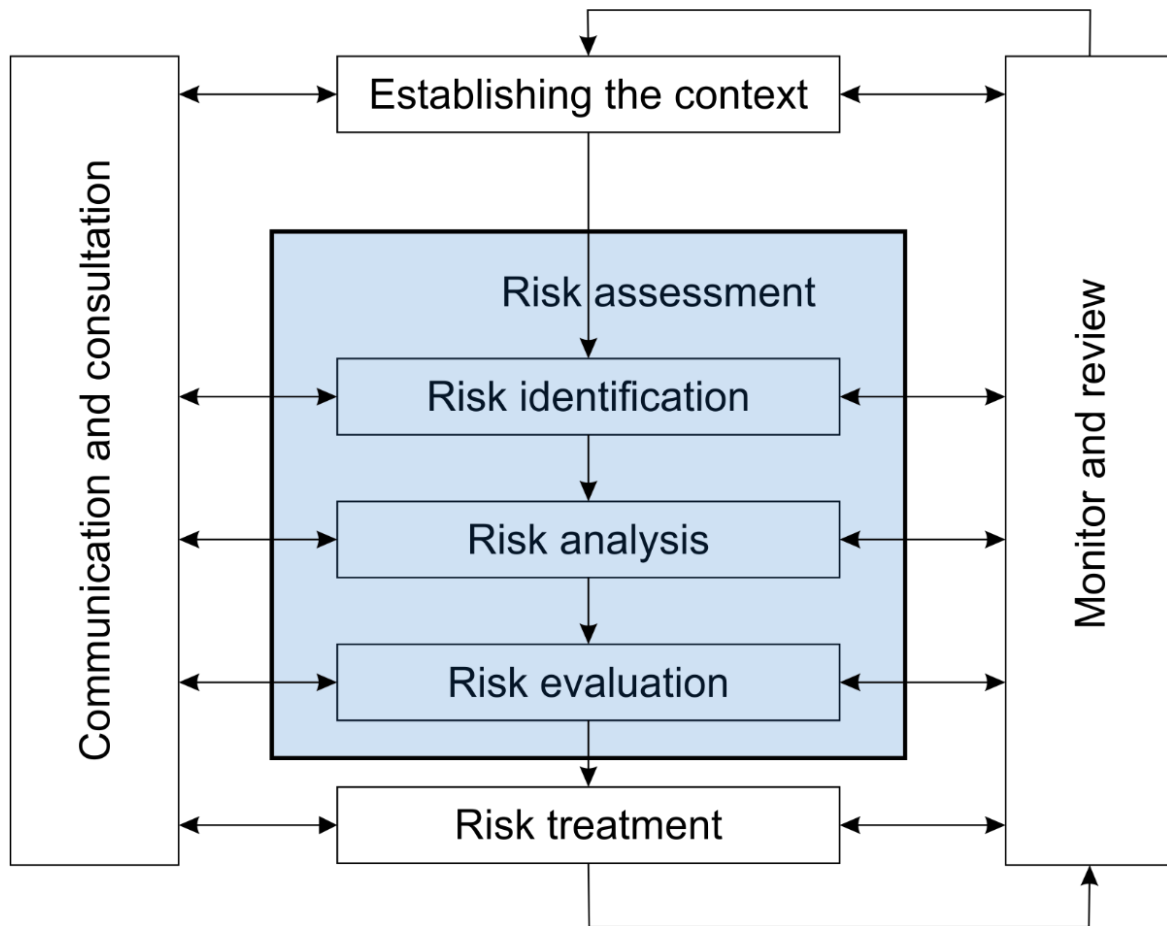


Figure 1.1: Risk management framework (adapted from *Standards New Zealand, 2009*).

Risk is defined by the following equation:

$$Risk = Hazard \times Vulnerability$$

A hazard can be defined as an event that interacts with society, potentially causing negative effects (UNISDR, 2009). ‘Hazard’ thus includes both the magnitude of the event and the probability of its occurrence during a specified time period. Vulnerability refers to the susceptibility of exposed community assets or populations to the negative effects of a hazard. Therefore, risk can be defined as the probability of occurrence multiplied by the consequences.

The risk management framework, as applied to an impact assessment for tsunamis, is as follows:

Establishing the context: This step involves establishing the objectives and scope of the study (Standards New Zealand, 2009).

Risk identification: This step involves identifying all the elements of risk, including the potential extent and magnitude of hazards and the likely consequences to society (Standards New Zealand, 2009). All exposed elements of society (e.g. buildings, infrastructure, and populations) are identified, and related to the hazard spatially and temporally. Hazards may also indirectly affect society (e.g. economic loss, stress). The vulnerabilities of the elements and how they may be impacted are considered.

In the context of tsunami impact assessments, the extent and magnitude of the hazard is typically based on inundation modelling of scenario events (Power, 2013a). The inundation modelling is based on reviewing the likely source of a major tsunami affecting a location, which is based on knowledge of past events and potential future sources (Grilli et al., 2015). The exposed assets and populations are identified by matching attributes contained within databases to the inundation modelling (Tarbotton et al., 2012; Valencia et al., 2011; Wood, 2009). The vulnerabilities and potential impacts are examined by a literature review of past events, such as the 2011 Great East Japan tsunami (Fraser et al., 2013). The risk identification step identifies the factors which require further analysis.

Risk analysis and evaluation: The identified risks are analysed further to develop a deeper understanding, for comparison and prioritisation (Standards New Zealand, 2009). The assessments follow a deterministic or a probabilistic approach, or a combination of the two.

Tsunami impact assessments usually follow a deterministic approach, based on specific tsunami scenarios, and typically follow the impact assessment process shown in Figure 1.2. The scenarios are based on modelling of previous events; scenarios with a specific source origin; or scenarios with a specific return interval. The vulnerabilities of exposed elements are analysed by reviewing literature of past events, and impact or vulnerability modelling (F. Dall’Osso et al., 2009; Valencia et al., 2011). Currently, most tsunami impact assessments are focused on building damage, using fragility or damage functions (Chapter 2; Tarbotton et al., 2015), or a relative vulnerability index (F. Dall’Osso et al., 2009; Tarbotton et al., 2012). The local context for the impact assessment needs to be considered, and information available from different contexts examined for suitability of application. Risk evaluation occurs after the risks are analysed, compared and prioritised, to determine whether the risk is acceptable or tolerable. The impacts may be assessed spatially and

temporally, allowing evaluation of the locations of assets or populations which will be the greatest focus for risk reduction.

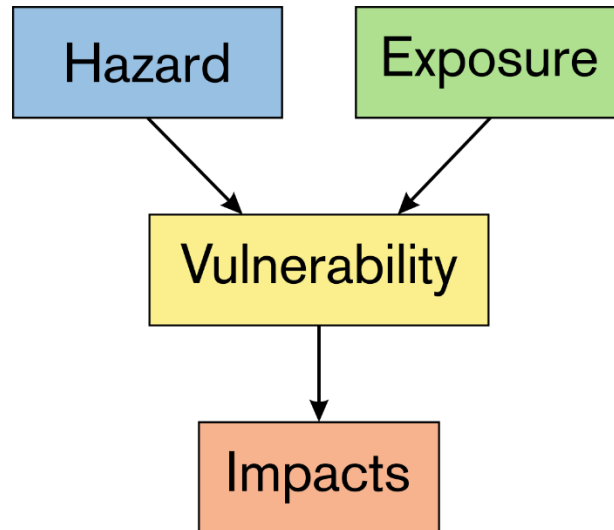


Figure 1.2: Impact assessment process. The hazard (e.g. inundation modelling) and exposure (e.g. building asset database) modules are related by considering the vulnerability of exposed assets to the hazard (e.g. using fragility functions), to produce outputs of the potential impacts.

Risk treatment: This step involves assessing treatment options for reducing risks (Standards New Zealand, 2009). Tsunami are largely uncontrollable events, with sea walls being one of the few direct mitigation options, although these are frequently impractical to construct and maintain, and can create a false perception of safety (F. Dall’Osso et al., 2009; Fraser et al., 2013; Suppasri et al., 2013b). Therefore, risk reduction primarily involves reducing the vulnerability of exposed elements (including people). This may be achieved through land-use planning, enhanced construction standards for buildings, evacuation planning, and education of the community regarding tsunami risk. Risk reduction initiatives may be focused on areas identified as being at significant risk following the impact assessment process, and where the benefits of treatment sufficiently outweigh the costs.

Monitor and review: This part of the framework is ongoing throughout all steps of the process, from establishing the context to risk treatment. It is important to use up-to-date information and data for risk management. For the tsunami impact assessment process, the most recent inundation modelling, exposed asset or population databases, and relevant

vulnerability assessment techniques should be used. As new information and data becomes available in the future, it is important to review the impact assessment process.

1.4 Research methodology and thesis structure

This thesis comprises four main chapters, with the risk management framework used as a conceptual basis throughout.

Chapter 1 establishes the context of the study, by detailing the aims and objectives of the thesis. The risk identification process starts by considering the tsunami hazard to Christchurch informed by literature review and modelled tsunami inundation scenarios (from Lane et al., 2014), and considering the potential impacts on physical assets, with a particular focus on buildings.

Chapter 2 deals with the assessment of building damage due to tsunami affecting Christchurch. For risk identification, a literature review is conducted to identify the vulnerabilities of buildings to tsunami, and investigate methodologies for impact assessment. The modelled tsunami inundation scenarios are combined with building asset information to identify the exposed assets, and the magnitude and extent of the hazard. Risk analysis is undertaken by examining and comparing existing asset databases of buildings within the inundation zone, creating an updated asset database, and modelling the impacts using fragility functions. Risk evaluation is undertaken by considering the outputs of the impact modelling, and the data are presented in various forms (e.g. tables and maps) for comparison and prioritisation. The impact assessment methodology, uncertainties, limitations, and recommendations are discussed.

Chapter 3 considers the assessment of building habitability and human displacement post-event. A similar process is undertaken to Chapter 2, beginning with a literature review of factors influencing residential building habitability and displacement of populations following natural hazard events, as part of the risk identification process. Interviews are also conducted to provide additional information, relevant to the local context. The risk analysis process is undertaken by modelling habitability and displacement spatially and

temporally, for the first week following the tsunami arrival. Risk evaluation follows the same general process as Chapter 2.

Chapter 4 draws conclusions and recommendations considering all aspects of the thesis.

A directly related MSc thesis entitled “Impact assessment of a far-field tsunami scenario on Christchurch City infrastructure” has been concurrently undertaken by James Williams, with a focus on the impacts on vital infrastructure such as transport links, water and sewerage systems, communications, and power supply. An MSc thesis entitled “Tsunami evacuation model for Sumner” was also concurrently undertaken by Lina Le. The same tsunami inundation modelling by Lane et al. (2014) was used for all three projects, however the theses are otherwise completely separate.

Both this thesis and that undertaken by James Williams are supported by Canterbury CDEM, Environment Canterbury, and NIWA. A \$5,000 stipend was provided by Environment Canterbury for these two theses. All three theses contribute to the RiskScope programme, which is a joint project between NIWA and GNS Science.

1.5 Literature Review

A literature review of the tsunami hazard to New Zealand, and specifically Canterbury, was conducted as part of the risk identification process. The tsunami inundation modelling for Christchurch that is used in this thesis is described. An overview of tsunami impacts on physical assets is also included, with a particular focus on the potential impacts on buildings.

1.5.1 Tsunami in New Zealand

New Zealand is exposed to multiple tsunami, including local- (less than one hour travel time), regional- (1 – 3 hours travel time) and distal-sourced (3 hours or more travel time) events (Power, 2013a). The largest events are typically caused by earthquakes on subduction zones beneath the ocean, which displace large volumes of water (GNS Science, 2014; Power, 2013a). For tsunami to be generated, the source earthquake is usually at least

M_s 7.0 (Bryant, 2008), and these are most likely to occur along subduction zones (King, 2015). Tsunami affecting New Zealand historically have also been caused by landslides (coseismic or otherwise) and volcanism, most notably by Krakatau in 1883 (De Lange and Healy, 1986; GNS Science, 2014). Figure 1.3 shows the regional and distant sources of tsunami that have affected New Zealand, as well as the subduction zones that may produce tsunami in the future. Figure 1.4 shows the locations of historical local tsunami sources, and the tectonic plate interface that is the most significant source of major local tsunami. It is estimated that New Zealand experiences a tsunami with a run up exceeding 1 m approximately every 10 years (Power, 2013a).

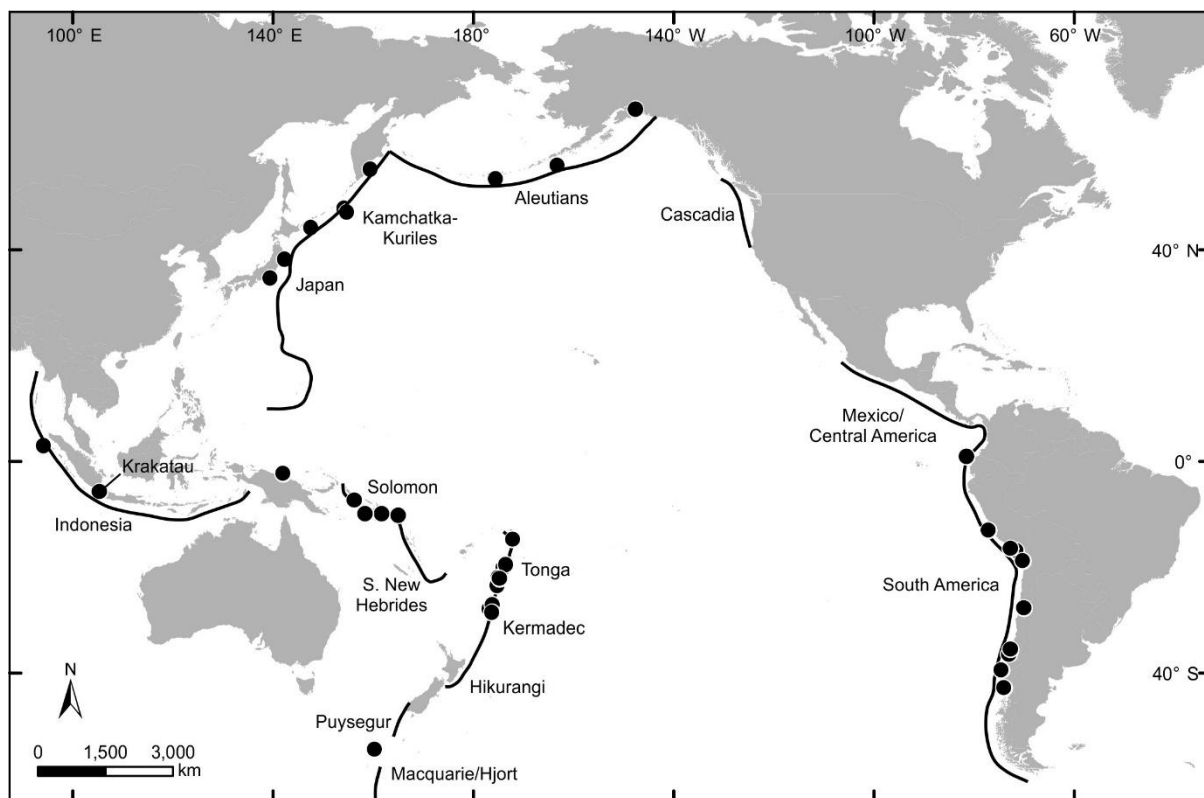


Figure 1.3: Source locations of regional and distant tsunami to have affected New Zealand historically (black dots), and subduction zones which may be future tsunami sources (black lines with labels). Adapted from data obtained from the New Zealand Tsunami Database (GNS Science, 2014).

Following the establishment of permanent European settlements in New Zealand (approximately 1835), and the beginning of reliable written records, the country has been affected by at least 80 tsunami (Power, 2013a). The events with the most widespread effects

occurred in 1868, 1877 and 1960, and all originated from large earthquakes in the Peru-Chile Subduction Zone off South America (GNS Science, 2014). These events impacted the entire eastern seaboard of New Zealand as well as the Chatham Islands, causing damage in low-lying coastal areas (De Lange and Healy, 1986; GNS Science, 2014). A significant local-source tsunami with a maximum run-up of 10 m was generated by the 1855 Wairarapa earthquake, causing flooding in Wellington and disturbing tides for up to a week (GNS Science, 2014; Power, 2013a). Two tsunami were generated off the coast near Gisborne in March and May 1947, that had maximum run-ups of 10 m and 6 m respectively (GNS Science, 2014; Power, 2013a). These tsunami affected only the nearby coastline, and were caused by slow rupture “tsunami earthquakes”, which produce disproportionately large tsunami given the source earthquake magnitude. The proposed mechanism for the source earthquakes of these events are subducting seamounts causing shallow ruptures in weak seafloor sediments, with slow rupture velocities allowing water to build up to a greater height (Bell et al., 2014). Additionally, between 35 and 40 paleotsunami events have been identified from geological evidence (Goff et al., 2010).

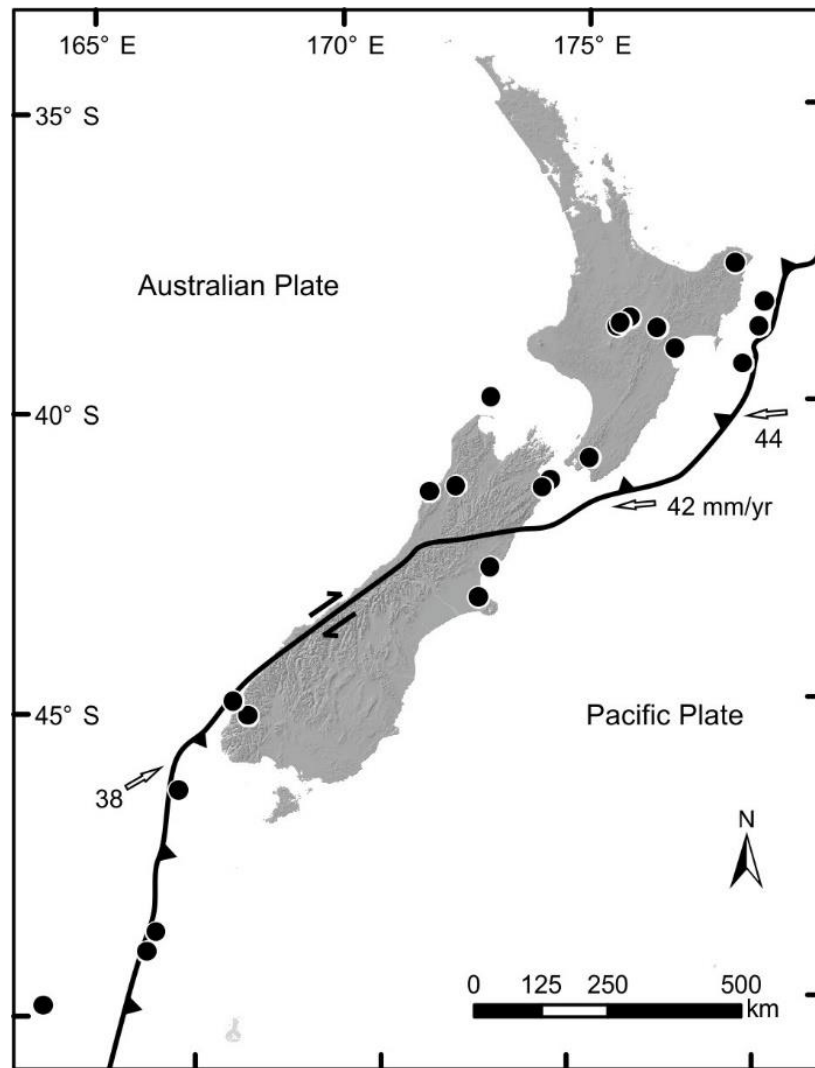


Figure 1.4: Source locations of locally generated tsunami during historical times (black dots), and the tectonic plate interface between the Australian and Pacific plates. Source locations include tsunami generated within inland bodies of water. Adapted from data obtained from the New Zealand Tsunami Database (*GNS Science, 2014*).

1.5.2 Tsunami in Canterbury

As with many other locations in New Zealand, Canterbury has been affected by several distant source tsunamis historically, including the events originating from South America in 1868, 1877, and 1960 (*GNS Science, 2014*). These events damaged coastal facilities such as wharves, jetties, and boatsheds as well as shipping (*GNS Science, 2014*). There was inundation of low-lying areas impacting bridges, residential buildings, roads and vulnerable structures such as fences. There were no deaths or injuries, however livestock losses were reported. The damage extended along much of the Canterbury coastline, with the most

severe damage occurring in the exposed coastal suburbs of Christchurch and communities around Banks Peninsula. Many historical tsunami events have coincided with low tide, reducing the severity of impacts.

The tsunami hazard in Canterbury is greatest from distant-source tsunami, particularly those originating from South America (Lane et al., 2014; Power et al., 2007; Power, 2013a). Canterbury is also exposed to tsunami originating locally and regionally, especially from offshore faults near Kaikoura and the Hikurangi Margin (Power et al., 2008). However a large tsunami is most likely to have a distant origin, based on probabilistic modelling (Power, 2013b). The most likely source is South America, particularly the subduction zone off the coast of Peru (Power, 2013b). The most recent distant-source tsunami to reach Canterbury occurred in September 2015, originating from the M_W 8.4 Illapel earthquake in Chile (Heidarzadeh et al., 2015), however the effect was small and no significant damage was reported.

1.5.3 Inundation modelling and scenarios

The most recent modelling of tsunami inundation for Canterbury from a distal source was performed by NIWA, and is based on an extreme event intended for evacuation planning and emergency management (Lane et al., 2014). The modelling was commissioned by Environment Canterbury (ECan), and is based on an event with a 2,500 year return interval, which is recommended by GNS Science for evacuation planning (Lane et al., 2014). This inundation modelling was chosen for the impact assessment modelling as it is the most recent modelling from a distal source, updated from older modelling created before the 2013 review of the tsunami hazard to New Zealand (Power, 2013a). Canterbury CDEM also requested that impact modelling be performed for a tsunami scenario with a South American source. The inundation modelling was provided by Emily Lane (NIWA) as a raster file containing water depths in metres for the study area. The inundation modelling constitutes the hazard module for the impact assessment process (Figure 1.2).

The tsunami source chosen is a M_W 9.485 earthquake occurring in the subduction zone off the coast of Peru, which has been identified as a major tsunami hazard source for a 2,500 year return period for the Canterbury coast (Lane et al., 2014; Power, 2013b). The

modelling assumed arrival of the largest wave coinciding with Mean High Water Spring (MHWS), and resulted in water levels between 4 and 10 metres above MHWS. The maximum flow velocities were between 2-3 m s⁻¹, except in river mouths where they were over 5 m s⁻¹. The areas modelled that are of interest for this thesis include the suburbs of coastal Christchurch, extending from approximately Waimairi Beach to Sumner and Taylor's Mistake (Figure 1.5). The arrival time of the first wave is between 14 – 15 hours after fault rupture, with the largest wave arriving between 17 – 20 hours after fault rupture. Waves will continue to arrive causing disturbances for at least 24 hours after the first wave arrival. The delay between fault rupture and first wave arrival should allow a sufficient timeframe for evacuation of the inundation zone to take place.

The hydrodynamic model used was RiCOM, which captures many of the physical aspects of tsunami inundation and is well-validated (Lane et al., 2014, 2011). The topographic data used for Christchurch were LiDAR data collected in 2011 following elevation changes due to the Canterbury Earthquake Sequence (CES). The bathymetric data include an open-ocean grid combined with NIWA coastal New Zealand bathymetry data (Lane et al., 2014).

The caveats and limitations of the modelling include uncertainties involving the source location, characteristics of the source fault rupture, and topographic and bathymetric data (Lane et al., 2014). The RiCOM modelling incorporates most hydrodynamic aspects of tsunami propagation and inundation, but also includes some simplifying assumptions (Lane et al., 2014). As the modelling was based on a 2,500 year return interval event and assumed the arrival of the largest wave occurred at the time of MHWS, the scenarios represent very extreme events, compared to the largest wave arriving at low tide.

The inundation modelling by Lane et al. (2014) consists of four scenarios originating from the same source location, although with slightly different source earthquake characteristics (fault length and orientation). The source earthquake magnitude is the same for all scenarios (M_w 9.485). The scenarios are titled Okada25A, Okada25B, Okada30 and Okada40, with the numbers referring to the vertical fault slip in metres. The source earthquake scenarios also have different lengths and widths of rupture. Each scenario has a slightly different inundation extent and flow depths within coastal suburbs of Christchurch. The Okada40 scenario is used primarily throughout this thesis, as it represents one of the more severe scenarios, with a relatively significant inundation extent

and maximum flow depths of up to 5 m within the Christchurch urban area. This scenario is also used to be consistent with impact and evacuation modelling by MSc candidates James Williams and Lina Le, respectively. The Okada25A, Okada25B, and Okada30 scenarios are also used within this thesis for comparison. The Okada40 scenario showing inundation extent and flow depths is displayed in Figure 1.5. Maps of the other three scenarios are shown in Appendix A.

The modelling by Lane et al. (2014) updates previous modelling based on a smaller tsunami scenario, which simulated an event originating from Peru in 1868 (Gillibrand et al., 2011). It was updated following the significant changes to coastal topography following the September 4, 2010 and February 22, 2011 earthquakes in Canterbury (Lane et al., 2012). The smaller scenario represents the worst-case distant source scenario based on historical data, and may have a return period of around 200 years (Gillibrand et al., 2011).

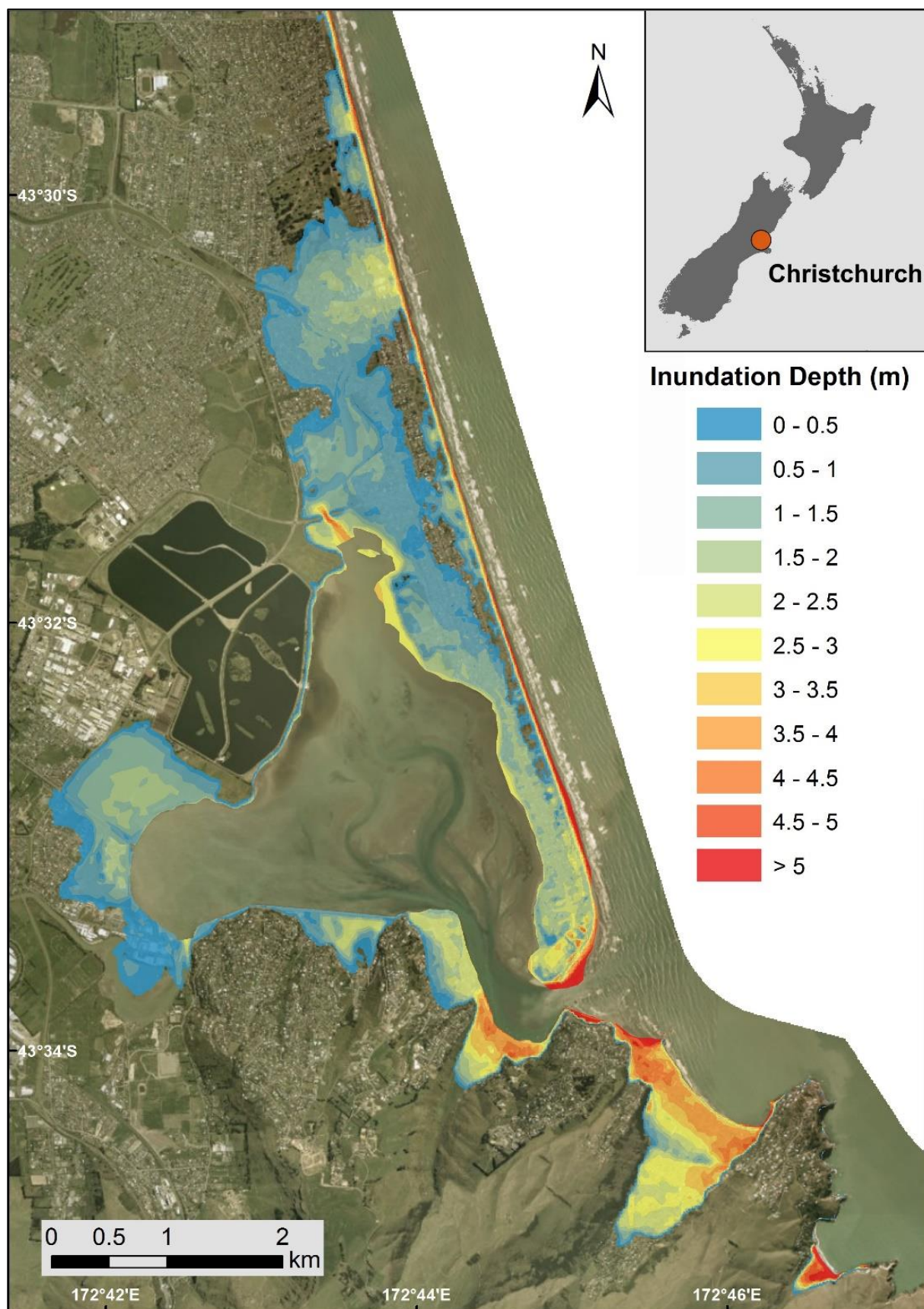


Figure 1.5: Inundation modelling of the Okada40 scenario for Christchurch, showing the inundation depths.

1.5.4 Tsunami impacts

The impacts of tsunami can be categorised as direct, indirect, tangible or intangible (Power, 2013a; Smith, 2013). The direct impacts generally include the immediate effects caused by tsunami inundation, such as structural damage, erosion or fatalities. Indirect effects are consequences of the event that are not due to the physical tsunami processes, such as displacement of people and disruption to services. Intangible effects are those which are not quantifiable, such as loss of investor confidence or quality of life (Power, 2013a). Of particular relevance to this thesis are the impacts on buildings, therefore the detail in this section is focused on those. Further details on the impacts on society, as relevant to habitability and human displacement, are discussed in the literature review in Chapter 3.

Damaging tsunami events in the 21st century have enabled researchers to survey the impacts in detail, and improve understanding of the relative importance of factors that contribute to structural damage (Leelawat et al., 2015, 2014; Leone et al., 2011). The direct effects of tsunami on buildings are primarily caused by the following:

- *Inundation*: Direct damage due to water contact, hydrostatic forces on structures
- *Currents*: Hydrodynamic forces acting upon structures
- *Scouring*: Erosion of foundations
- *Buoyancy*: Uplift of structures, especially beneath floor levels, and flotation of materials
- *Debris*: Impact of entrained materials, such as materials from collapsed buildings, vehicles and trees

The individual influence of each of these contributing factors is difficult to isolate, and may vary significantly between events and locations (Tarbotton et al., 2015, 2012). The only factor that is practicable to directly measure is inundation depth (Koshimura et al., 2010). Although water velocities can be estimated from numerical modelling, they are not necessarily accurate (Tarbotton et al., 2015). Debris is expected to play a strong role in the impact on structures, however there are currently no models developed for these effects (Charvet et al., 2014a; Tarbotton et al., 2015).

Several attributes of buildings are particularly important for estimating tsunami impacts. Construction type is the most fundamental attribute, with the majority of damage surveys recognising its significance (Charvet et al., 2014a; Leelawat et al., 2014). Common classifications of construction type include wood, masonry, steel and reinforced concrete, with a general trend of decreasing susceptibility to damage from tsunami, from the former to the latter. This is observed regardless of the location or event surveyed, although overall construction standards vary greatly. For example, several studies have indicated an inundation depth of 2 m will destroy a wooden house (Cousins et al., 2007; Ruangrassamee et al., 2006; Schmidt et al., 2007; Shuto, 1993; Suppasri et al., 2013a), whereas reinforced concrete buildings can withstand much greater depths (Reese et al., 2011; Ruangrassamee et al., 2006; Valencia et al., 2011).

The number of storeys also contributes significantly to the susceptibility of a building, with taller buildings being less vulnerable. This may be explained by the increased structural strength to resist gravity loads required for taller buildings (Suppasri et al., 2013a). This attribute is particularly important for buildings constructed of wood or steel, which are usually 3 storeys or less (Leelawat et al., 2014). For example, wooden houses exposed to 3 m of inundation depth in the 2011 Great East Japan tsunami had damage probabilities of 0.75, 0.6 and 0.4 for one, two and three storeys respectively (Suppasri et al., 2013a).

The vulnerability of a building is also related to the function of the building, with similar designs used for similar purposes (Leelawat et al., 2014). For instance, residential buildings with wooden frames are typically constructed to a similar standard, as are steel framed factory buildings. Additionally, the shape and orientation of a structure affect the susceptibility to damage (F. Dall’Osso et al., 2009). For example, an open structure that allows water to pass through may survive inundation from a tsunami (Thusyanthan and Madabhushi, 2008).

Other factors that may influence the impact to buildings include the presence of protective barriers (e.g. seawalls, control forests, other buildings), topography, and the condition of a structure before an event (F. Dall’Osso et al., 2009; Leelawat et al., 2014; Suppasri et al., 2013b). The impact assessment modelling for estimating building damage employed in this thesis incorporates the most significant factors that may be quantified, including inundation depth, construction type and number of storeys.

Chapter 2: Assessment of building damage

2.1 Introduction

Major tsunami events affecting an urban area have the potential to inflict considerable damage to buildings, and estimating the extent and degree of damage from a tsunami scenario is an important factor for emergency management planning. The coastal urban area of Christchurch contains a mix of residential, commercial and other building purposes; and the structures are of varying building materials and heights. The building attributes influence the vulnerability of the structures to the effects of tsunami (Suppasri et al., 2013b; Tarbotton et al., 2015). The impact of a tsunami event to buildings can be assessed by considering the vulnerability of the exposed assets to the hazard intensity, and producing estimates of the probable degree and distribution of damage. An impact assessment of building damage allows emergency management to estimate areas where planning and resources may be focused. Building damage is also a key influential factor for determining whether a building is habitable (Chapter 3).

The objectives of this chapter are to assess the impact to buildings from a far-field tsunami scenario; contribute to the RiskScape programme by improving the building asset database and investigating the use of fragility functions for estimating building damage; and produce resources for use in emergency management planning and scenario exercising. A literature review was conducted of impact and vulnerability assessments to inform the impact modelling process and determine the most appropriate fragility function for use in the Christchurch context. The methodology includes examining currently available building asset databases; creating an up-to-date building asset database for the study area; and impact modelling for estimating the damage to buildings using ArcMap and Excel. The impact modelling results are presented in various forms, including maps and tables, which are intended to constitute a comprehensive set of resources for different emergency management purposes, as well as for comparing different modelling approaches. Finally, a discussion of the results and methodology is presented.

2.2 Literature review

A literature review was conducted to summarise the approaches currently used for tsunami impact assessments. This included a detailed review of currently available damage and fragility functions for tsunami impacts on buildings, which form an important part of the impact assessment process. Use of the RiskScape tool for tsunami impact assessments is also summarised. The literature review within this chapter builds upon the summary of impacts to buildings which is presented in Chapter 1. The literature review forms part of the risk identification process within the risk management framework.

2.2.1 Impact and Vulnerability Assessments

Assessing the impact of a tsunami on an urban environment requires relating the hazard intensity to attributes of the exposed assets. Impact assessments are categorised as either *ex ante* (conducted before an event, usually using a deterministic scenario or sometimes probabilistically considering the hazard) or *ex post* (conducted following an event, often focused on collecting empirical field-based or remotely sensed data). Information from *ex post* assessments is typically used as the basis for *ex ante* assessments, as well as to validate models produced before or after an event (Power, 2013a). Ideally, a situation in which both *ex ante* and *ex post* assessments were undertaken would provide the best information for comparison and validation of assessment techniques. The concept of detailed impact assessments incorporating the vulnerability of structures to tsunami hazards has only begun to gain widespread interest following the 2004 Indian Ocean Tsunami (IOT), due to the severe impacts of this event and a lack of empirical measurements of hazard intensity or building damage before this time (Synolakis and Bernard, 2006). Therefore there are as yet no examples of a detailed pre- and post-event assessment for a single impacted location. Instead, impacts from case-study events (such as the 2004 IOT) are used to develop vulnerability and fragility functions for asset class types (e.g. building construction type) which can be used to conduct impact assessments for other scenarios. The asset classes are generally quite broad, due to small sample sizes of collected data and the high degree of uncertainty. Impact assessments may also include estimates of human casualties,

environmental damage, economic costs, damage to infrastructure and other asset classes. This chapter is focused on the damage to buildings, which is relatively well-addressed in the literature.

There is no standardised methodology for tsunami impact assessments, and a variety of techniques have been implemented or proposed. These are based on qualitative, semi-quantitative or quantitative approaches, which each have pros and cons (Table 2.1). Of relevance to this thesis are quantitative and semi-quantitative approaches, the majority of which incorporate the use of Geographic Information Systems (GIS). In contrast to qualitative assessments which have a tendency to be subjective, quantitative analysis is more comparable between events and may be used for a cost-benefit analysis when investigating possible risk reduction measures (Power, 2013a).

Table 2.1: The pros and cons of different approaches for impact assessments (adapted from Power, 2013).

Methodology	Pros	Cons
Qualitative	Can be based on sparse or coarse data; efficient	Relatively subjective; cannot easily be used to compare events
Semi-quantitative	Improves on qualitative by adding scores/rankings	Requires more data than qualitative assessment
Quantitative	Used for deterministic or probabilistic modelling; provides in-depth information; can be used for cost-benefit analysis	Data intensive; results depend heavily on quality of input data

Quantitative ex post impact assessments may include field surveys of damage and hydrodynamic tsunami attributes, aerial photography interpretation of tsunami impacts, numerical modelling to simulate a tsunami event (to provide hydrodynamic tsunami attributes in locations not directly surveyed), or a combination of approaches. Ex post impact assessments are particularly useful for determining the relative influence of factors contributing to damage, and reproduction of observed impacts using geospatial models is

a common approach (Fraser et al., 2013; Gopinath et al., 2014; Marchand et al., 2009). Of particular importance is the use of ex post impact assessments to develop fragility and damage functions (see page 23).

The general process for quantitative ex ante impact assessments (Figure 2.7) includes modelling of the hazard, determining the assets which will be exposed and assessing the vulnerability of the assets (Koshimura et al., 2010). Modelling of the tsunami hazard for a given location is usually performed on the basis of one or a few potential scenarios (deterministic modelling). The scenarios are typically based on the knowledge of past tsunamis at a location (either experienced during recorded history or from paleotsunami evidence), the potential tsunami sources and the estimated probability of occurrence. Inundation modelling reveals the assets that are exposed to the hazard, and may also provide hydrodynamic parameters (such as inundation depth) which can form part of the vulnerability assessment for the exposed assets. Various data sources may be used, such as impact assessments for similar locations (Usha et al., 2012), topographic analysis (Najihah et al., 2014; Sinaga et al., 2011), or historical tsunami observations (Omira et al., 2010). An alternative to deterministic modelling is probabilistic modelling, which considers the probability of the hazard occurring over a specified time period for a given location. The results can be presented in terms of losses, fatalities or injuries estimated for different return intervals, and different source locations of the hazard. For example, Horspool et al. (2015) modelled the probabilistic risk for various cities within New Zealand, producing loss curves, such as for direct property loss shown in Figure 2.1.

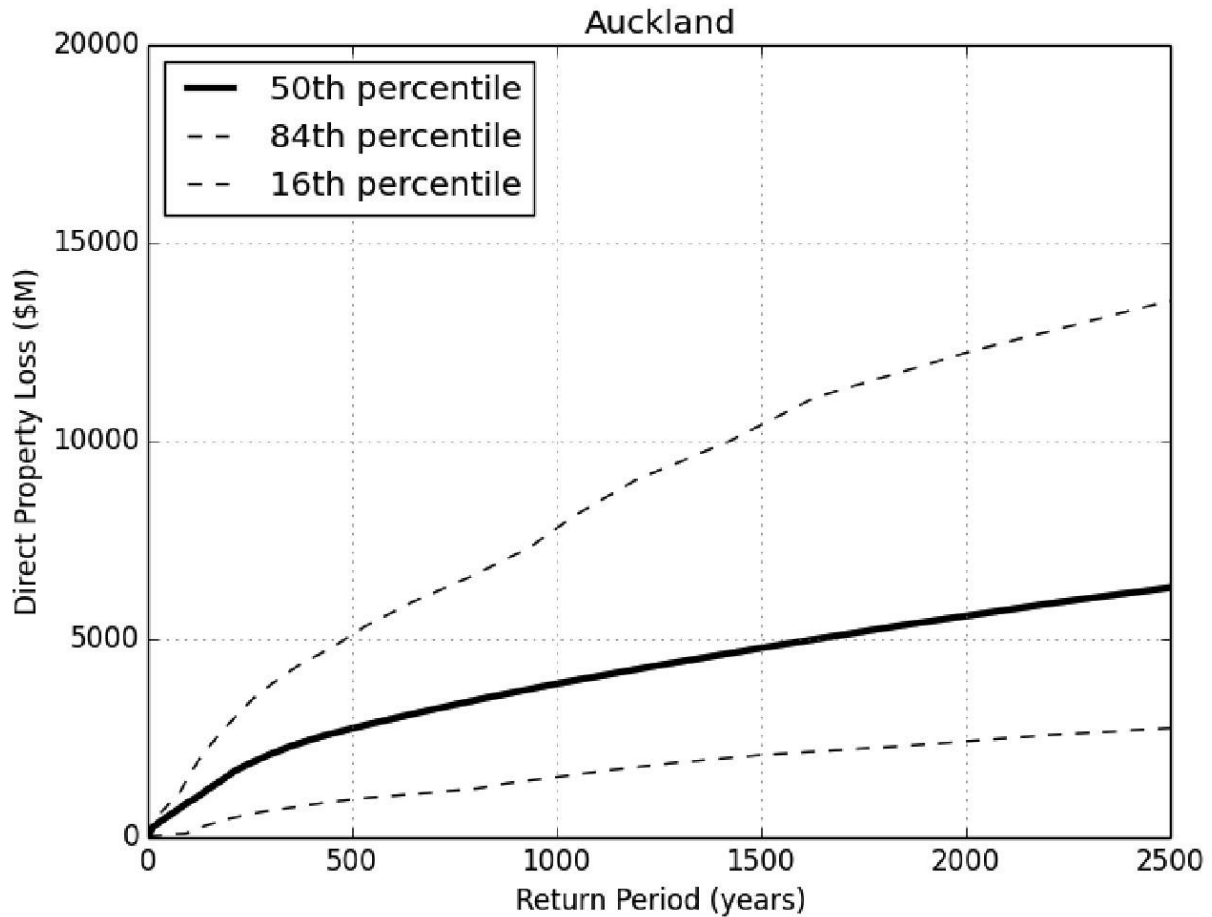


Figure 2.1: Example of loss curve from probabilistic modelling, for direct property loss in Auckland due to tsunami (from (Horspool et al., 2015))

One of the most comprehensive approaches for assessing the vulnerability of buildings is the Papathoma Tsunami Vulnerability Assessment (PTVA) model, which is a semi-quantitative method first proposed in 2003 (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003). The model is designed to incorporate all known factors which significantly contribute to building vulnerability, such as construction type, number of stories, shielding, and the influence of debris. A weighted scoring system is applied to each factor of vulnerability, depending on the relative importance of each factor for determining the vulnerability of a building. A Relative Vulnerability Index (RVI) score is produced for each building individually, which can then be mapped (Figure 2.2). The latest iteration of the model is PTVA-3, which incorporates additional factors that influence the vulnerability of structures compared to earlier models, based on improved understanding of building vulnerability gained following the 2004 Indian Ocean tsunami (F. Dall’Osso et al., 2009). The weighting given to each contributing factor of vulnerability is also improved. The

PVTA-3 model has applied to part of the coastline in Sydney, Australia (F Dall’Osso et al., 2009). It has also been validated by applying the model to the Aeolian Islands, Italy, and comparing the results with field survey data following a landslide-induced tsunami that impacted the area in 2002 (Dall’Osso et al., 2010). Although the model is considered fairly robust and accurate, a large amount of data is required, which makes it impractical for application to large areas when resources are limited (Tarbotton et al., 2015, 2012). The RVI scores produced are generally only useful for comparing the relative vulnerability of buildings within a local area. PVTA-3 also relies on many qualitative attributes, therefore the model has limited suitability for quantitative impact assessments that are comparable to other studies. Future work on the PVTA-3 model may incorporate more quantitative measures such as fragility functions to improve upon the current qualitative aspects of the scoring system (Tarbotton et al., 2015, 2012). For the purposes of this thesis, a more quantitative impact assessment is required, and therefore an approach incorporating fragility functions is desirable.

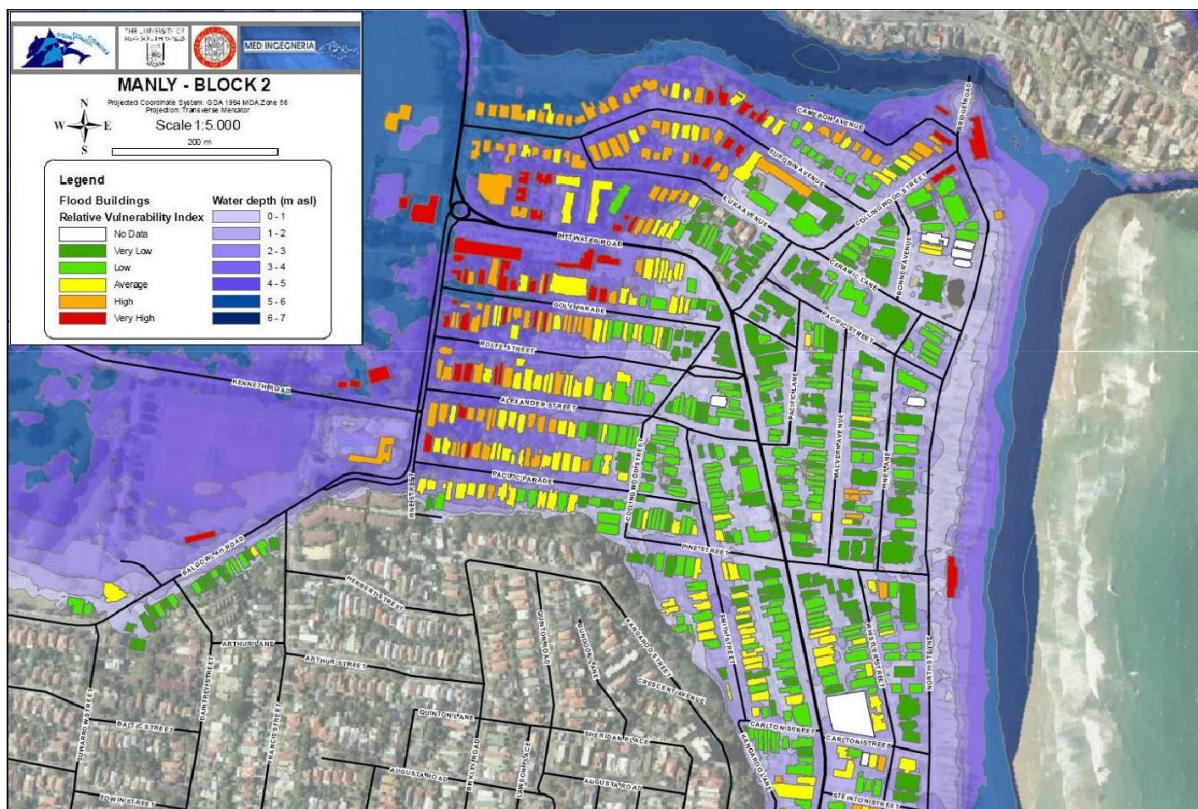


Figure 2.2: Tsunami water depth and Relative Vulnerability Index applied to buildings in Manly, Sydney, based on the PVTA-3 model (from Dall’Osso et al. 2009).

2.2.2 Fragility and damage functions

Fragility functions (or fragility curves) for tsunami estimate the probability of damage or fatalities relative to a hydrodynamic parameter of a tsunami, such as inundation depth, current velocity or hydrodynamic force (S Koshimura et al., 2009; Power, 2013a). A recently developed fragility function for multiple construction types is shown in Figure 2.3. Damage functions are also related to hydrodynamic parameters, and estimate the damage ratio of a structure relative to replacement cost, or may be expressed as damage levels (e.g. from minor damage to collapse) or as a scale of relative intensity. An example of a damage function is shown in Figure 2.4. Both types of function may be used for vulnerability assessments of the potential impact of tsunami inundation for a given location and scenario. A summary of currently available fragility and damage functions is provided in Table 2.2.

2.2.2.1 Function development

One of the earliest damage functions for tsunami was developed by Shuto (1993) based on examination of data from historical tsunami in Japan (Koshimura et al., 2009). The damage function is a tsunami intensity scale, relating the observed height of a tsunami to the level of damage to buildings of different construction types. Shuto (1993) found that wooden houses were the most susceptible structure type, masonry houses withstood greater tsunami heights, and reinforced concrete buildings were the least susceptible to damage. More recent tsunami damage and fragility functions generally agree with Shuto's (1993) assessment of the relative strengths of construction types against the effects of tsunami inundation.

Although fragility functions have been in use for estimating structural damage due to earthquakes for several decades (Schultz et al., 2010), the development of tsunami fragility functions was first introduced by Peiris (2006), using data obtained following the 2004 Indian Ocean tsunami in Sri Lanka (Tarbotton et al., 2015, 2012). The impacts on buildings were surveyed by the Sri Lankan Department of Census and Statistics, and categorised into three damage states (partial–usable, partial–unusable and complete), and six depth bins.

Cumulative distribution functions were created across the depth bins for each damage state, providing the cumulative probability of a building reaching each damage state dependent on the inundation depth. Dias et al. (2009) expanded on the work of Peiris (2006) by dividing the fragility functions into those with $>50\%$ or $<50\%$ permanent structures, to assess the influence of construction type (Tarbotton et al., 2015).

Further development of fragility functions was undertaken by Koshimura et al. (2009), producing fragility functions for buildings and fatalities, estimating the probability of collapse and death respectively. Remotely sensed data on the damage state of structures (from satellite imagery taken after the event) and the number of deaths (recorded per village) were combined with information on the hydrodynamic attributes of the tsunami (from numerical tsunami modelling) using GIS analysis. The probability of structural damage or fatality was calculated by determining the ratio of collapsed buildings or deaths to survival, within bins relating to various hydrodynamic features. For example, approximately 1000 buildings were counted in bins of roughly 0.2 m of inundation depth. Regression analysis of the probabilities allowed the discrete data sets to be developed into fragility functions. The general methods employed by Koshimura et al. (2009) have formed the basis for more recent fragility function and damage function development.

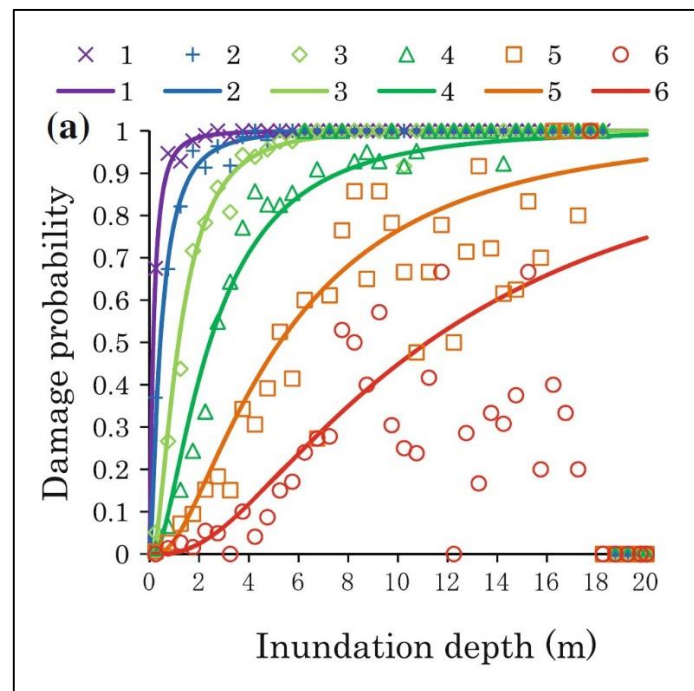


Figure 2.3: Example of a fragility function for reinforced concrete structures, showing six different damage states (from Suppasri et al. 2013a)

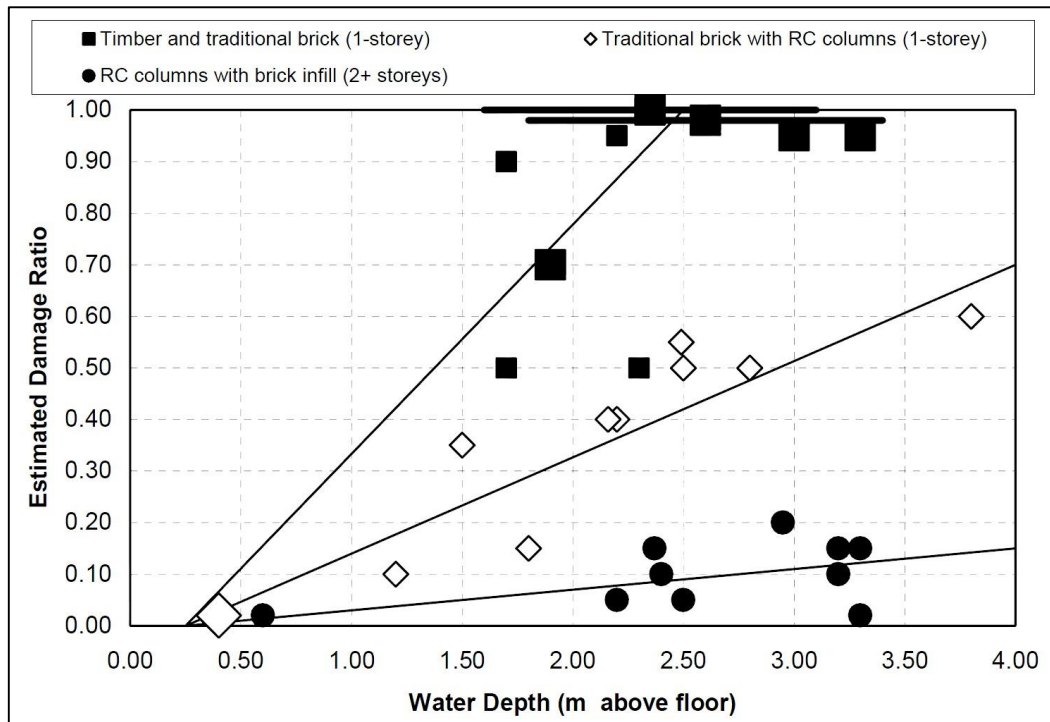


Figure 2.4: Example of a damage function, for different construction types (from Reese *et al.* 2007).

A variety of data sources for function development are used, including field surveys, remote sensing, numerical modelling of a tsunami event and historical documentation. Data sources are chosen based on resources and the ability to acquire information following an event.

- *Field surveys:* The majority of published literature on function development for tsunami incorporates data collected during post-event field surveys. Field surveys may collect data on the hazard, exposure, or impact. Structural damage within the inundation zone is examined, typically noting construction type and the degree of damage according to a pre-defined damage scale. Measurements of inundation depth are also taken in some surveys. For example, following the South Pacific tsunami which affected Samoa and American Samoa in 2009, Reese *et al.* (2011) recorded structural damage according to a five-state damage scale (“Minor” to “Collapse”), also categorising buildings by construction type. Inundation depth was measured at various points, before being interpolated across the survey area using GIS. Field survey data provide the most accurate and comprehensive information on tsunami impacts, but are frequently limited by a lack of resources and access to

affected areas following tsunami events. The number of observed buildings is therefore often relatively small, and may adversely affect the accuracy of developed fragility functions. An exception is the field survey data collected following the 2011 Great East Japan tsunami, in which over 250,000 buildings were surveyed, allowing more reliable fragility functions to be derived from the data (Charvet et al., 2014a; Suppasri et al., 2013a).

- *Remote sensing:* Multiple studies have used remotely sensed imagery (predominantly satellite) taken before and after tsunami events to determine the structures that have been damaged following a tsunami. Remote sensing is also able to be used for hazard, exposure and impact data collection. A significant advantage is the ability to cover a wider area than may be possible during field surveys. However, it is difficult to determine the level of damage to a structure based on vertical imagery alone. For function development relying heavily on remote sensing data, damage states are usually limited to collapsed/washed away versus survived (Koshimura et al., 2009; Mas et al., 2012; Suppasri et al., 2011). Satellite image interpretation is often verified by comparison with field survey data collected on the ground.
- *Numerical modelling:* Numerical modelling to simulate the inundation caused by a tsunami is occasionally used to provide the hydrodynamic parameters of a tsunami. In the development of fragility functions, modelling is used to reproduce the effects of a tsunami event that has taken place. For example, Koshimura et al. (2009) modelled the 2004 IOT using the source earthquake characteristics, to simulate the inundation depths and current velocities experienced in Banda Aceh, Indonesia. Numerical modelling can be validated by inundation depths measured during field surveys, and aerial imagery which shows the inundation extent. The modelling can provide data on areas that were not directly surveyed, and also have the additional advantage of allowing the estimation of parameters such as the current velocity and hydrodynamic force. Numerical modelling is limited by the quality of input data, simplifying assumptions and resolution of output data (Lane et al., 2014; Power, 2013a).

- *Historical documentation:* Fragility and damage functions have also been developed using data on tsunami height and structural damage collected following historical tsunami events. For example, Shuto (1993) used this approach investigating data available from past events affecting Japan. Due to uncertainty in the accuracy of the data collected, functions developed from historical data are only particularly useful for estimating damage caused during the events they are based on, for example when wave heights are mentioned in descriptive accounts but observations on structural damage are absent (Koshimura et al., 2009).
- *Analytical techniques:* Fragility functions may also be developed using analytical techniques, as proposed for tsunami by Macabuag and Rossetto (2014). Fragility functions of this type are based on the structural response to a tsunami intensity parameter. They may be created for structure types in which no empirical data are currently available, however no analytical fragility functions are available yet, as the process for creation is at an early stage.

2.2.2.2 Applications

Fragility and damage functions for tsunami have only been developed in recent years, as a result of increased interest in the ability to provide accurate damage and casualty estimates for locations where a significant tsunami risk is present. Most functions rely on limited datasets collected following damaging 21st century tsunami events, and the applicability of a function to a given location is highly dependent on the construction type of buildings. Although the broad categories of construction type are often similar among studies (e.g. wood, masonry, steel, reinforced concrete), building standards vary greatly between locations. For New Zealand, fragility functions developed using data collected following the 2011 Great East Japan Tsunami (GEJT) are the most relevant, due to similar building standards that require construction to withstand frequent seismic activity. Additionally, the robustness of fragility studies are limited by small sample sizes. However, the data collected from the 2011 GEJT includes a very large number of surveyed buildings (>250,000), with information on construction type and damage state, greatly increasing the utility of the fragility functions developed (Charvet et al., 2014a, 2014b; Suppasri et al., 2013a).

Several studies have incorporated fragility or damage functions into their vulnerability assessments. Valencia et al. (2011) developed their own damage functions based on data from Banda Aceh, Indonesia, and adapted them to a European context. The purpose of this study was to develop damage functions that could be used for estimating tsunami damage to buildings along the Mediterranean coast. Care was taken to use data on buildings that were comparable in construction type and number of storeys to buildings within the coastal Mediterranean context. To produce damage maps of test sites (Setubal, Portugal; Mandelieu, France; Catania, Italy; Balchik, Bulgaria; Rabat, Morocco), the damage functions were converted into thresholds for application in GIS software, and combined with building asset point data and numerical tsunami inundation modelling. Wiebe and Cox (2014) used numerical modelling of potential tsunami scenarios in combination with fragility functions to estimate structural damage in Seaside, Oregon, USA. This location was chosen as a test site for assessing the potential damage from a Cascadia subduction zone tsunami. Fragility functions developed following the 2011 GEJT were considered the most appropriate, due to a similarity in construction type between the two countries. Fraser et al. (2014) estimated structural damage for Napier, New Zealand given a variety of local tsunami scenarios. The authors used fragility functions developed using data from Japan (Suppasri et al., 2013a), Chile and American Samoa (Mas et al., 2012), again because of similar construction type. Both studies by Fraser et al. (2014) produced damage estimates that were similar.

Although considerable effort has been applied to developing fragility and damage functions, there are relatively few published studies using them to date. The studies which have used the functions are typically only examples of how they may be applied to a test location. This is likely due to the considerable resources necessary to develop the building asset databases necessary for application of fragility and damage functions, and because functions for tsunami damage to buildings have only recently begun to be produced to an adequate standard.

2.2.2.3 Limitations

There are many limitations to the accuracy of empirically derived fragility and damage functions published to date, particularly due to the source data used and the damaging aspects of tsunamis that are not incorporated into the functions. Although some studies provide functions with current velocity and hydrodynamic force as demand parameters, functions using inundation depth are the most reliable as this parameter is less affected by the inaccuracies of tsunami inundation modelling (Koshimura et al., 2009). This is due to numerical modelling of inundation depth being able to be validated using field survey data, whereas other hydrodynamic parameters are very difficult to estimate in the field. Additionally, parameters such as current velocity and force are very spatially variable, and numerical modelling is often not at high enough resolution to adequately estimate the parameters at a given asset location.

Most fragility functions are developed by fitting a linear statistical model to damage data aggregated into bins, which is unable to properly incorporate high or low damage probabilities, and can affect the shape of the curve, especially at the tails (Tarbotton et al., 2015, 2012). Charvet et al. (2014a) used generalised linear models to develop fragility functions which address these issues.

Existing fragility functions for tsunami generally do not explicitly consider the influence of factors such as mobilised debris, shielding and scouring. This is due to the relatively poor understanding of the influence of these factors, and the complication of computationally modelling the effects. However, fragility functions implicitly incorporate these factors, as the buildings surveyed following an event which are used for function development have been affected by many factors, even if the function only has a single demand parameter such as inundation depth (Tarbotton et al., 2015, 2012).

Fragility functions are generally more accurate at predicting damage to wooden structures compared to steel or reinforced concrete, the latter types having a large amount of uncertainty even when derived from large datasets, particularly at higher inundation depths and probabilities of damage (Charvet et al., 2014a). This may be due to greater variation in how the latter types of buildings are constructed compared to wooden structures, however no specific details are provided in Charvet et al. (2014a).

2.2.2.4 Application to Christchurch context

Despite having some caveats, using fragility functions for an impact assessment scenario for Christchurch is the most appropriate vulnerability model to use. In comparison to the PVTa-3 assessment model, less detailed data are adequate, which is important when considering an area the size of the coastal urban area of Christchurch. Using an asset database of buildings within the inundation zone, fragility functions can readily be applied to a variety of numerically modelled scenarios. The most recently developed and accurate functions are based on data from Japan (Suppasri et al., 2013a; Tarbotton et al., 2015), and are reasonably transferrable for assessment of local structures (Fraser et al., 2014). Additionally, the fragility functions developed by Suppasri et al. (2013) are intended to be incorporated into the RiskScape software, which would allow comparison of the results from this thesis with those produced by RiskScape.

Table 2.2: Summary of fragility and damage functions

Reference	Location (event)	Function type	Hydrodynamic Parameters	Variables	Damage states	Data
(Charvet et al., 2014a)	Japan (2011 GEJT)	Fragility	Inundation depth	Structure type: Wood, Steel, Reinforced Concrete (RC)	Six-state damage scale	Field survey (178,448 buildings)
(Charvet et al., 2014b)	Ishinomaki, Japan (2011 GEJT)	Fragility	Inundation depth	Structure type: Wood, Masonry, Steel, RC Different terrain types within Ishinomaki city	Five-state damage scale	Field survey (56,950 buildings)
(Gokon et al., 2014)	American Samoa (2009)	Fragility	Inundation depth, current velocity, hydrodynamic force	Structure type: Mixed	Four-state damage scale	Satellite image interpretation, numerical modelling, field survey (451 buildings)
(Suppasri et al., 2013a)	Japan (2011 GEJT)	Fragility	Inundation depth	Structure type: Wood, Masonry, Steel, RC, Mixed Number of storeys: Wood, RC Topography: Plain coast & Ria coast	Six-state damage scale	Field survey (251,301 buildings)
(Mas et al., 2012)	Chile (2010)	Fragility	Inundation depth	Structure type: Wood, Masonry, Mixed	Survived / washed away	Satellite image interpretation, field survey (915 buildings)
(Valencia et al., 2011)	Banda Aceh, Indonesia (2004 IOT)	Damage level	Inundation depth	Structure type: Light, Brick/masonry, Brick with RC columns and masonry infill, Non-engineered RC	Five-state damage scale	Field survey, satellite image interpretation (2,576 buildings)
(Leone et al., 2011)	Banda Aceh, Indonesia (2004 IOT)	Fragility and damage level	Inundation depth	Structure type: Wood, Brick, Brick with RC columns, Non-strengthened RC, Strengthened RC	Six-state damage scale	Field survey, satellite image interpretation (6,200 buildings)
(Suppasri et al., 2011)	Phang Nga and Phuket, Thailand (2004 IOT)	Fragility	Inundation depth, current velocity, hydrodynamic force	Structure type: Wood, RC, Mixed	Destroyed / not destroyed	Satellite image interpretation, numerical modelling (4,596 buildings)

Reference	Location (event)	Function type	Hydrodynamic Parameters	Variables	Damage states	Data
(Reese et al., 2011)	Samoa and American Samoa (2009)	Fragility	Inundation depth	Structure type: Generic, Timber residential, Masonry residential, RC residential Shielded/unshielded and debris-impacted/non-impacted for masonry residential	Five-state damage scale	Field survey (201 buildings)
(Murao and Nakazato, 2010)	Sri Lanka (2004 IOT)	Damage ratio	Inundation depth	Structure type: Solid / non-solid Solid: RC and steel Non-solid: Wood and Masonry	Four-state damage scale	Field survey (1,535 buildings)
(S Koshimura et al., 2009; Shunichi Koshimura et al., 2009)	Banda Aceh, Indonesia (2004 IOT)	Fragility	Inundation depth, current velocity, hydrodynamic force	Structure type: Mixed	Destroyed / survived	Satellite image interpretation, numerical modelling, field survey, historical data (~33,000 buildings)
(Reese et al., 2007)	Java, Indonesia (2006)	Damage ratio	Inundation depth	Structure type: Timber/bamboo, Brick traditional, Brick traditional with RC columns, RC with brick infill Shielded vs. exposed buildings	Damage ratio	Field survey
(Ruangrassamee et al., 2006)	Thailand (2004 IOT)	Damage level	Inundation depth, distance from shore	Structure type: RC	Four-state damage scale	Field survey (94 buildings)
(Dias et al., 2009; Peiris, 2006)	Sri Lanka (2004 IOT)	Fragility	Inundation depth	Structure type: Residential	Three-state damage scale	Field survey
(Shuto, 1993)	Historical tsunamis affecting Japan	Damage level	Inundation depth	Structure type: Wooden, Masonry, RC	Three-state damage scale	Field survey, historical data

2.2.3 RiskScape

RiskScape is a joint research programme between GNS Science and NIWA with an aim to understanding the impacts and risks associated with natural hazards (King and Bell, 2009; Schmidt et al., 2011). One of the main outputs of this research programme is the RiskScape software, which is an open-source multi-hazard loss-estimation tool. The RiskScape software is a work in progress, with a new version expected to be released in 2016. An objective of this thesis is to contribute to the improvement and development of the software, and the research based on the current version will feed into the new version. As this thesis is focused on the RiskScape software, the term “RiskScape” used throughout this thesis generally refers to the software as opposed to the wider programme, unless otherwise specified.

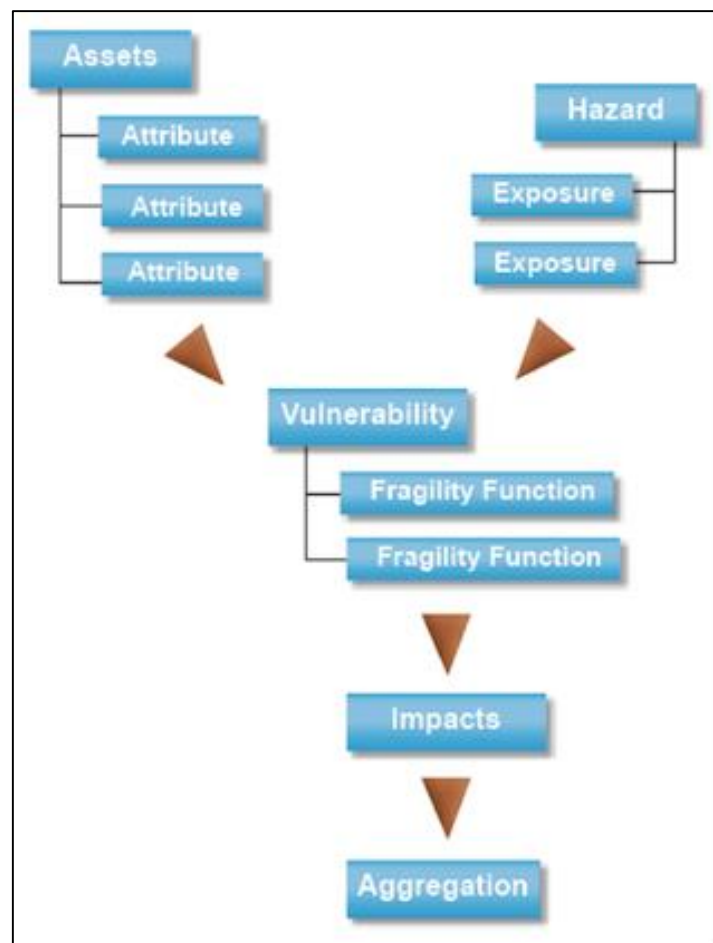


Figure 2.5: The RiskScape process (from *GNS Science/NIWA*, 2014).

RiskScape combines hazard, asset and vulnerability modules to estimate the impacts and losses (King and Bell, 2009). The outputs are contingent on the available vulnerability models, and may include estimations of damage state, replacement cost, functional downtime, displacement of populations and the number of injuries or deaths (Schmidt et al., 2011; Wright et al., 2011). The results are aggregated spatially, for example by suburb, census area unit, or 1 km² grid squares. The general process is shown in Figure 2.5, and is the same impact assessment process used in this thesis (Figure 2.7). The exported results may be mapped or imported into other GIS systems for further analysis. Tsunami is one of the hazards included within the software.

2.2.3.1 Using RiskScape for tsunami impact assessment

For estimating the impacts and losses from tsunami in RiskScape, a selection of numerically modelled tsunami scenarios are available, for various locations around New Zealand. The building asset database covers the entire country, and contains the relevant attributes for tsunami impact estimation, such as construction type, number of storeys and floor height. However, the asset database is limited by the accuracy of source data, and the requirement to statistically fill missing data in some places (see pages 38 & 39). Vulnerability and losses for tsunami are currently calculated using a damage function developed by Reese et al. (2007), based on field survey data from the 2006 tsunami affecting Java, Indonesia. The damage function was created using building damage data from a location that is very different from the New Zealand context. This is expected to be updated in the future to a fragility function developed by Suppasri et al. (2013) using data from the 2011 GEJT.

2.2.3.2 Using RiskScape to model tsunami impacts in Christchurch

Modelling the impacts of tsunami on Christchurch buildings is possible in RiskScape using one of the four modelled far-field tsunami scenarios for Canterbury (see page 11) by Lane et al. (2014), in combination with the available building asset database for Canterbury. There are currently a number of limitations to modelling tsunami impacts for Christchurch in RiskScape. Most importantly, there is a need for the vulnerability module to incorporate

the most appropriate fragility functions available, specifically those developed by Suppasri et al. (2013a). The accuracy of the building asset database within the Christchurch City inundation zone currently available within the software requires assessment. Even small errors within the database, such as an inaccurately listed floor height, could significantly reduce the accuracy of the outputs. The inability to export the hazard module and disaggregated outputs into other GIS software is also a disadvantage. An objective of this thesis is to improve the impact modelling process and the accuracy of the outputs where possible. As the current version of the RiskScape software did not have the more recent fragility functions built in, the impact modelling of building damage was performed using ArcMap and Excel.

2.3 Methodology

2.3.1 Overview

A broad overview of the methodology for assessing the impact to buildings due to a major far-field tsunami scenario is shown in Figure 2.6. The assessment of available asset databases, creation of an up-to-date asset database and impact modelling are part of the risk analysis process within the risk management framework. This section addresses the thesis objectives of modelling the impact to buildings, and assessing and contributing to the improvement of RiskScape.



Figure 2.6: Overview of the building damage impact assessment methodology.

2.3.2 Impact assessment process

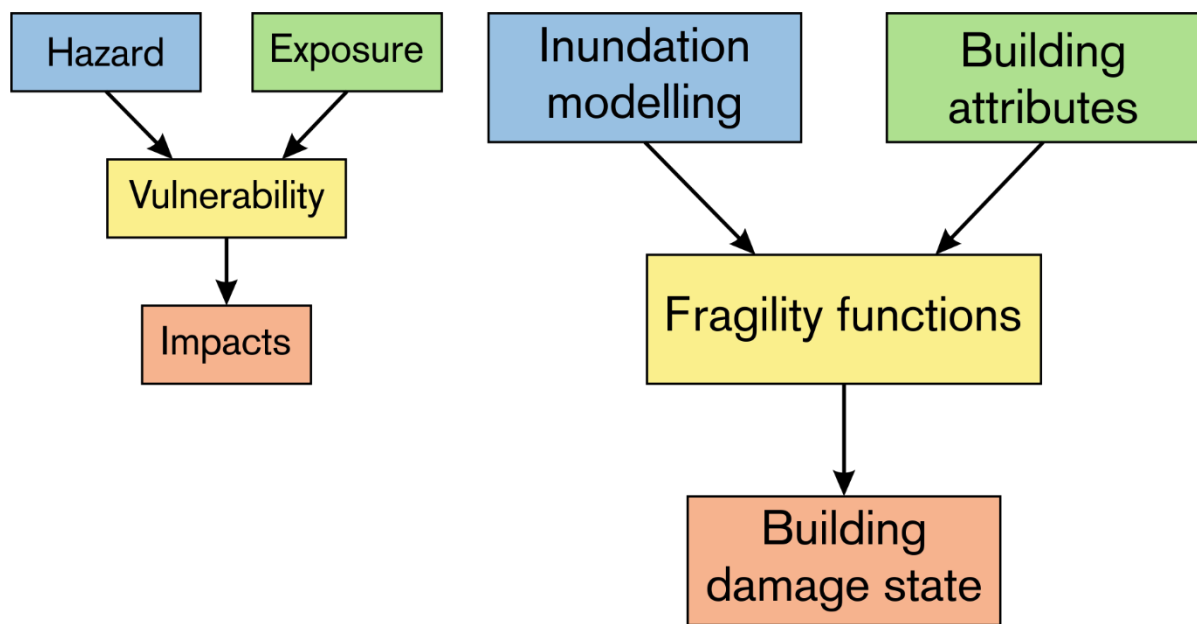


Figure 2.7: Impact assessment process (left), and the specific impact assessment process for tsunami damage to buildings (right).

The impact assessment process as it applies to assessing tsunami damage to buildings is shown in Figure 2.7. For this project, the hazard model input consists of four modelled tsunami inundation scenarios from a South American source (see page 11). The key attribute of the tsunami modelling is the inundation depth at each point within the inundation zone. The exposure model input is the asset database of building locations and attributes, which was created using data collected during field surveying of the inundation zone, and processing using GIS software. The vulnerability model input is the fragility functions developed by Suppasri et al. (2013), which match the inundation depth with the relevant building attributes to assess the probability of damage.

2.3.3 Creating a database of building assets

2.3.3.1 Overview

An essential part of the impact assessment process is an accurate database of assets within the affected area. This allows the pairing of the hazard information (specifically the inundation depth) with building attributes, to generate damage probabilities or damage states using fragility functions. The building purpose (e.g. commercial, residential or public) is also an important attribute for assessing results. A flow chart of the process for creating the asset database is shown in Figure 2.8.

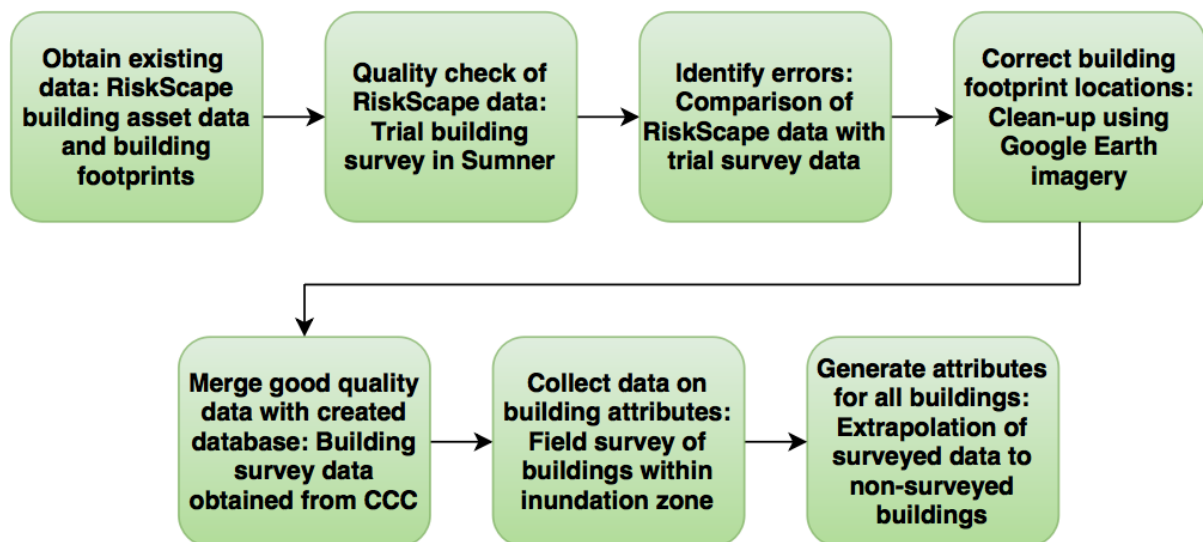


Figure 2.8: Overview of the process for creating the asset database of buildings.

The attributes that are relevant to this project and were collected during surveying are:

- Construction type
- Number of storeys
- Ground floor height
- Building purpose (use category)

2.3.3.2 The RiskScape building asset database

The RiskScape programme has developed an asset database for Canterbury buildings, which includes all built-up areas within the inundation zone. The database contains information on building attributes including (but not limited to) structural information, building purpose, number of occupants, contents value and replacement cost (Paulik, 2015). The RiskScape asset database was created primarily using data purchased from Quotable Value NZ (QV), and combined with building footprints provided by local councils (King and Bell, 2009). Population data are sourced from the 2013 census, administered by Statistics New Zealand.

The QV data were used as they cover all of New Zealand, but some data are incomplete, inaccurate or uncertain (King and Bell, 2009). The QV data are relatively old, and were obtained prior to the Canterbury Earthquake Sequence (CES), which significantly altered the building stock within the inundation zone due to building demolitions and reconstruction. To examine how accurate the RiskScape database is within the inundation zone, a trial field survey was conducted to compare the observations with the existing dataset.

2.3.3.3 Trial field survey of Sumner buildings

Several coastal blocks of the suburb of Sumner were chosen within which to conduct a trial survey. This part of Sumner was selected because of the mix of building types, for both construction type and building purpose. The area surveyed included several residential blocks, as well as most of the commercial area of Sumner (Figure 2.9). The trial survey was intended to be fairly representative of the building assets present within the wider inundation zone. A sufficient number of buildings needed to be surveyed for comparison with the RiskScape asset database, and to assess the time required for field surveying. The surveying was done using an Excel spreadsheet containing the building locations and attributes from the RiskScape database. The key attributes of relevance to the project were observed and compared to the existing attributes. Figure 2.9 shows the buildings observed during the trial field survey. Approximately 200 buildings were surveyed, taking about 4 hours to do so. The survey was conducted on 3rd June, 2015.

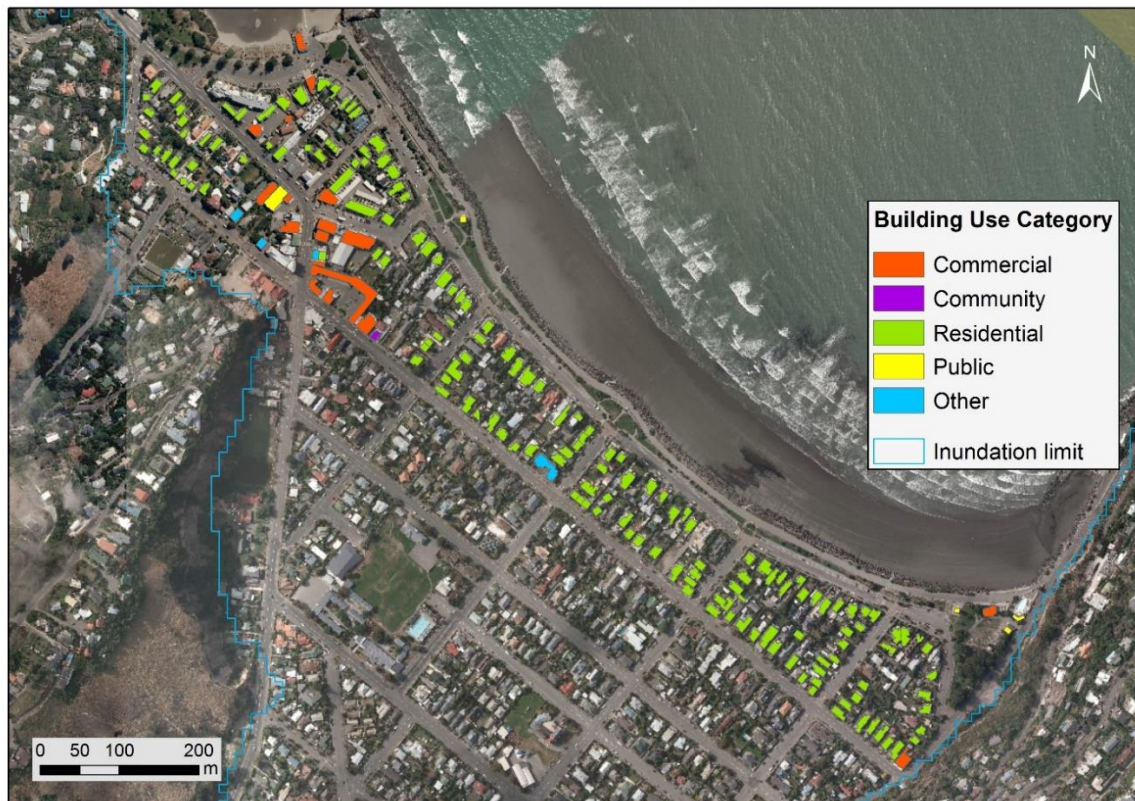


Figure 2.9: Sumner trial building survey area, showing the use category of buildings surveyed.

2.3.3.4 Identified problems with RiskScape database

A number of issues with the RiskScape building database were identified following the trial field survey of Sumner, and examination of the building attributes in Excel and GIS software. A comparison of statistics between the RiskScape database and the trial field survey is shown in Table 2.3.

- The building locations were overlaid on the most recent Google Earth imagery (dated 9/1/2015), where it was identified that many buildings which had been demolished following the CES were still present within the RiskScape database.
- Some buildings were missing from the database, including some that had existed prior to the CES.
- The number of storeys was calculated as the ratio of the floor area to the footprint area, which does not truly represent the number of storeys and is not appropriate

for use with fragility functions. For example, a building with a floor area of 300 m² and a footprint of 200 m² would have a ratio of 1.5, which is then used as the “number of storeys” attribute. However it does not truly represent the number of storeys, which should always be an integer. Although the decimal value may be rounded to the nearest integer, this is not as accurate representation of the true number of storeys.

- Some buildings were not designated to the correct use category e.g. commercial buildings listed as residential dwellings.
- There are many small structures that were classified as residential buildings, such as sheds and garages. These are not appropriate for inclusion in the database as they were not typically occupied, and the fragility functions used are intended for use with more substantial structures.
- The attributes of construction type and floor height above ground were often incorrect or inaccurate, partly due to the QV data being provided to RiskScape as an aggregated dataset (King and Bell, 2009). This is because the QV data have been disaggregated and distributed across building point locations, and do not necessarily represent the true attributes at any individual site.

Table 2.3: Comparison of statistics for the RiskScape building database and trial field survey of Sumner.

Attribute	RiskScape building database	Sumner trial field survey
Mean floor height (m)	0.424	0.337
No. of residential buildings	175	160
No. of commercial buildings	14	17
No. of demolished buildings	13	
No. of buildings with incorrect construction type	27	

In order to improve the data for this area and provide updated information for RiskScape, it was decided to create a new database using up-to-date building footprints and field survey data.

2.3.3.5 Field survey of buildings

To create an accurate database of building attributes, field surveys of buildings within the inundation zone were conducted. Firstly, a plan was created of areas and transects to be surveyed (Figure 2.10), which was intended to be representative of the building stock within the inundation zone. The main commercial areas of New Brighton and Ferrymead were chosen to be surveyed due to the importance of local businesses and organisations to the functioning of the community, and therefore accurate data on these buildings are valuable. The commercial area of Sumner was mostly included within the trial survey. The surveying transects run mostly through residential areas of the inundation zone. These were designed to capture a significant portion of the residential building stock, and include buildings from most of the suburbs that receive widespread inundation.

Within the Ferrymead and New Brighton commercial areas, all buildings were surveyed, where data were not already present in the structural building survey database obtained from Christchurch City Council (CCC, Table 2.4). The database provided by CCC contains data on building attributes collected during thorough building surveys, by engineers following the CES. The database was provided as building footprints with the attribute data attached. There was no need to survey these buildings again, as all the relevant information was provided.

For the surveying along transects, buildings on both sides of the street were surveyed. Generally, an attempt was made to survey each building that was close to the street, however this was not always possible due to high fences, trees and other obstacles obscuring the view of some structures.

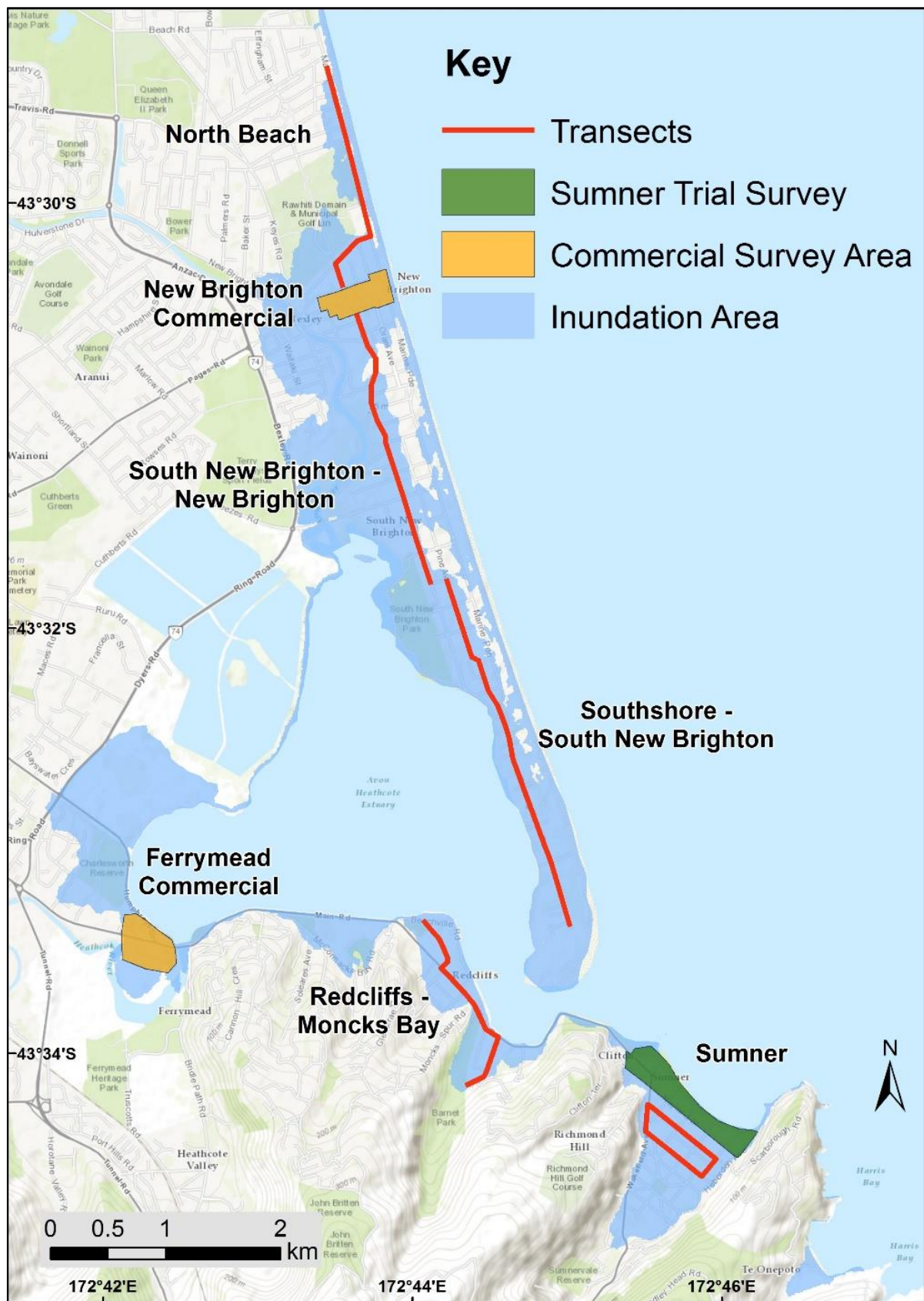


Figure 2.10: Areas and transects traversed for field survey of buildings. All buildings within the commercial areas that did not already have data available were surveyed.

The surveying was carried out using the RiACT application (developed by GNS Science), which is a tool for the Android software platform for use on smart phones and tablets, designed to capture building attribute data for RiskScape (Lin et al., 2014). RiACT is capable of capturing a large variety of attributes (entered into pre-determined fields based on observations or measurements), however only the key attributes for the project (construction type, number of storeys, ground floor height and use category) were collected. The main user interface of the application is shown in Figure 2.11.

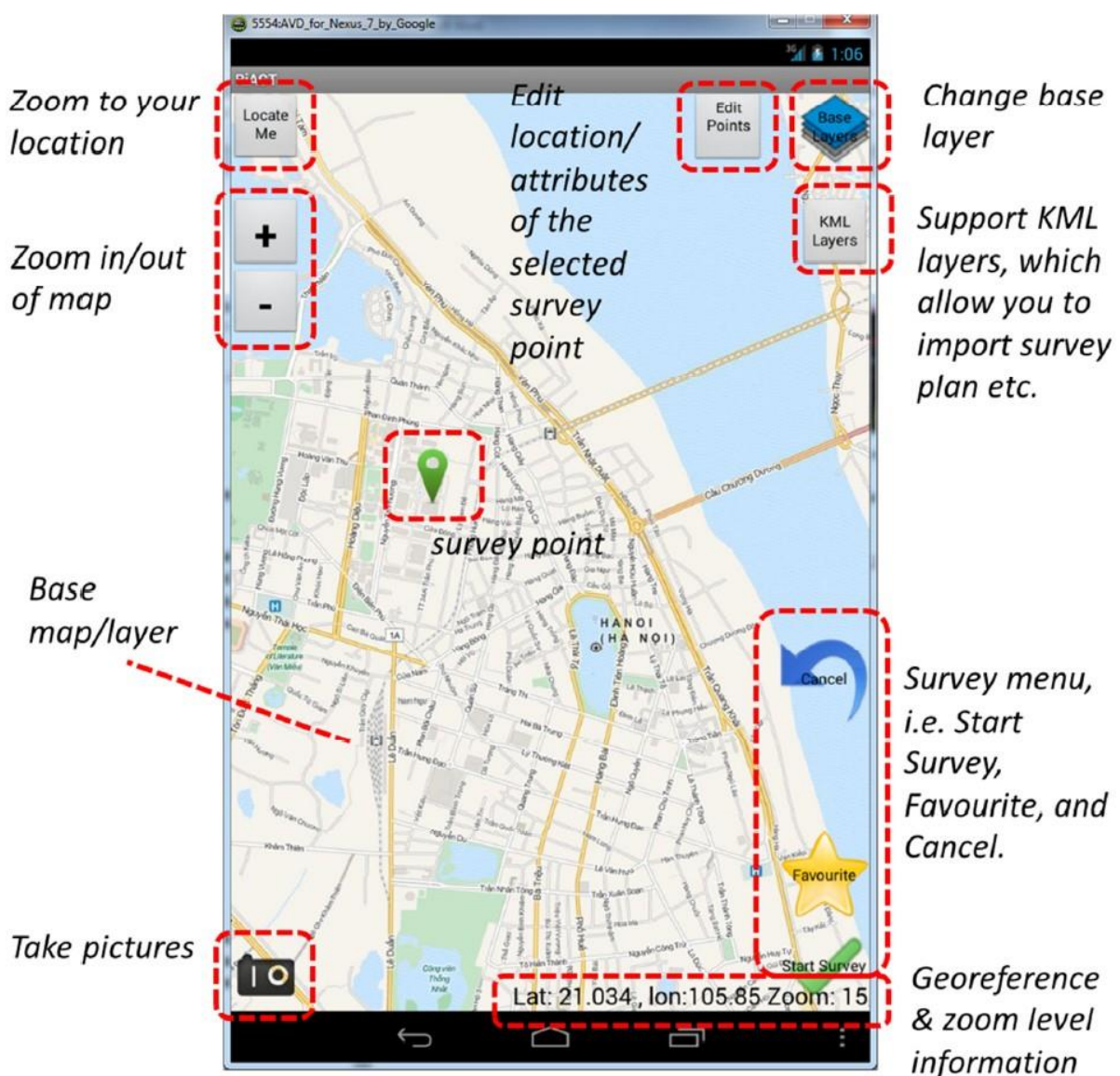


Figure 2.11: The RiACT application interface (from Lin et al., 2014).

The process of surveying with RiACT involves selecting a building point location, and entering the relevant attributes of the building based on observations. It is necessary to be accurate when locating a building, in order to match the survey points to building footprint data. Incorporated into the application were tiled maps of Christchurch which were used to assist in locating buildings, in addition to the location provided by GPS on the devices used (Samsung tablets and a smartphone). Building footprint data (in the form of a Google Earth .kml file) were also downloaded and overlaid on the maps.

Once a building is located accurately within the RiACT application, the required attributes are recorded based on observations. The “number of storeys” and “use category” (building purpose) attributes were usually straightforward to record via observation. The “construction type” attribute was also usually apparent, however due to the requirement for buildings to only fit within one category (e.g. wood or reinforced concrete construction), occasionally the construction type was recorded based on an estimation of which material was most prominent. It was necessary to record only one construction type per building as the fragility functions used for the impact assessment modelling require distinct categories. The “ground floor height” attribute was estimated based on observation from the street, as direct measurements were not possible due to access restrictions.

Over 1200 buildings were surveyed, out of approximately 6500 buildings (based on footprints, see page 46) within the newly-created asset database. Most of the non-residential buildings were surveyed, if data were not already available and if the buildings were observable from the street. Approximately 1070 residential buildings were surveyed, representing a significant portion of the residential dwellings within the inundation zone. It was not possible to survey all buildings within the study area due to time and access constraints. The field survey of buildings was conducted on 5 separate days, between 13th - 28th August, 2015. The surveyed building point locations and attributes were matched with the updated building footprints as part of the GIS processing (section 2.3.3.6).

2.3.3.6 GIS methods for creating the asset database

The various data sources used for creating the asset database are shown in Table 2.4. An overview of the GIS process is displayed in Figure 2.12, with most actions being performed in ArcMap (version 10.3.1) unless otherwise specified.

Table 2.4: Data sources used for creating the building asset database.

Data type	Data source	Details	Use within database
Building footprints	Christchurch City Council (CCC)	Building footprint polygons which form the basis of building locations	Building locations and mapping
Building asset database for Christchurch	RiskScape	Building point and attribute data that is the current asset module in the RiskScape application	Comparison with created database
Post-earthquake structural survey of buildings	Christchurch City Council	Mainly commercial, community or facility buildings surveyed by engineers post-2011	Building attribute data
Aerial imagery	Google Earth	Pre and post-earthquake imagery showing the difference in building stock (latest imagery used dated 1/9/2015)	Post-processing of building footprints to create up-to-date database
Building attributes	Field surveying using the RiACT application	Attributes collected: building location, construction type, number of storeys, height of floor above ground, building purpose	Building attribute data

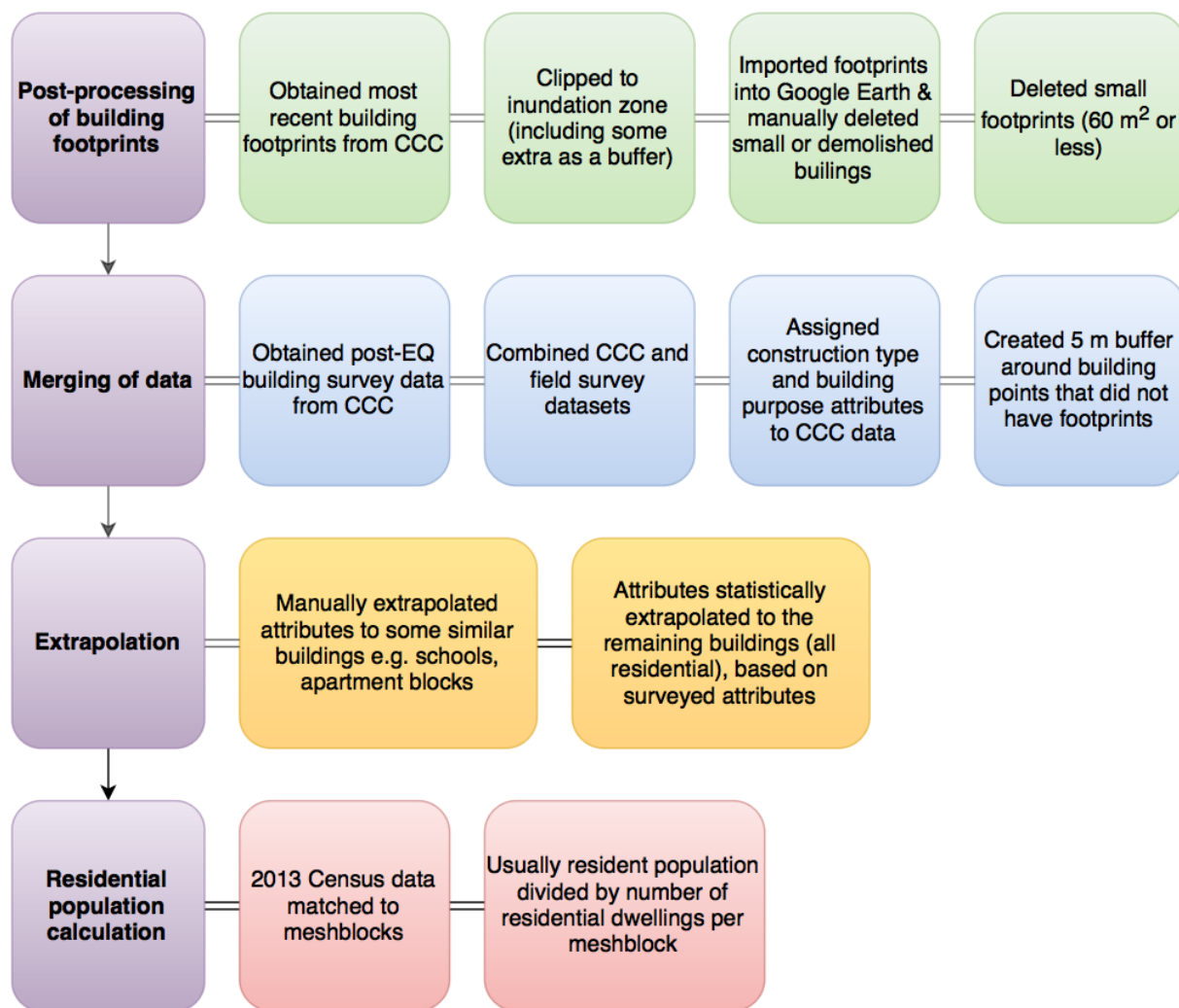


Figure 2.12: The main GIS process used during the creation of the asset database.

2.3.3.7 Post-processing of building footprints

Post-processing of the CCC building footprint database was necessary as the existing dataset was out-of-date, particularly as many buildings have been demolished following the CES. The largest number of demolitions occurred in the residential “red zone”, incorporating the suburb of Bexley and the area near the Avon-Heathcote estuary, however there were also many demolished buildings scattered throughout all suburbs within the inundation zone. The CCC building footprints were imported into Google Earth, and the most recent available imagery (dated 9/1/2015) was used to delete missing buildings. Small buildings were also deleted manually where it was clear that they were garages or sheds. Most structures 60 m² or less were automatically deleted in ArcMap, with the exception of residential buildings that were observed to be part of apartment blocks.

2.3.3.8 Merging of data

The field survey and CCC datasets were merged once the field surveying and post-processing of building footprints was complete. The CCC dataset contained many attributes (>100) that were not directly relevant to the impact assessment modelling, and therefore these attributes were deleted. Although the attributes for “number of storeys” and “ground floor height” were explicitly listed within the CCC dataset, the “construction type” and “use category” attributes had to be determined based on several related categories. For example, the construction type was manually determined by considering categories containing structural attributes (e.g. beam, wall, and column construction material). The field survey and CCC datasets, containing building attribute data, were combined with the building footprints.

2.3.3.9 Extrapolation

Following the merging of the field survey and CCC datasets, there were many remaining buildings footprints without attribute data (5115, out of a total of 6494 buildings in the database). The data from building footprints which had attributes were extrapolated to building footprints without attributes.

Firstly, this was carried out manually for some buildings, such as schools and apartment blocks. In these cases, where it was likely that buildings nearby were of similar types (determined using Google Earth, Maps and Street View), the attributes of the buildings for which data were available were copied to those that only had footprints. For example, schools often have several buildings that are of similar construction type, number of storeys and ground floor height. Only the buildings visible from the street were able to be surveyed, therefore the attributes of those surveyed buildings were manually extrapolated to the remaining buildings within the school property.

The field surveying areas and transects (section 2.3.3.5) were created to collect attributes for almost all non-residential buildings. Therefore, once the manual extrapolation of attributes to identified non-residential buildings (determined using Google Earth and Maps) that could not be directly surveyed was complete, all remaining building footprints

within the database were considered to be residential. The attributes for these buildings were extrapolated statistically, based on the attributes of the surveyed residential dwellings. For construction type and number of storeys, this was carried out using “discrete” random number generation in Excel. This method preserves the same proportion of attributes for the extrapolated dataset as the surveyed dataset (e.g. 72% are single storey wooden buildings, 3% are 2-storey concrete masonry). The ground floor height was generated for each building based on the mean and standard deviation of the dataset. A summary of the numbers of buildings for each data source is shown in Table 2.5.

Table 2.5: Summary of the number of buildings for each source of attribute data within the database.

Data source	No. of buildings
Field survey	1205
CCC Post-EQ data	174
Manually extrapolated	109
Statistically extrapolated	5006
Total	6494

2.3.3.10 Residential population calculation

To determine the number of people per residential dwelling, the Statistics New Zealand 2013 census data and meshblocks were used. Meshblocks are the smallest geographical units which are used by Statistics New Zealand for data collection, covering all of New Zealand (Statistics New Zealand, 2016). The census data first had to be joined to the meshblock polygons, based on meshblock number. For all meshblocks fully contained within the newly created asset database, a count was made of the number of residential buildings. The number “usually resident population” (9,834) was then divided by the number of residential buildings (4,502), giving a value of 2.184 residents per household within the inundation zone. This compares with a national average of 2.7 residents per

household (Statistics New Zealand, 2014). The lower value within the inundation zone may be due to reduced population following the CES, particularly at the time of the most recent census (5th March, 2013), as well as the low proportion of medium-high density housing within the study area. The calculated value has been used for population estimates, including displacement of people (Chapter 3).

2.3.3.11 Comparison of asset databases

Once the creation of the new asset database was complete, a comparison was made with the existing RiskScape database. The number of buildings per construction type is shown in Table 2.6, and a summary of build purposes is provided in Table 2.7. The summaries are based on the number of buildings within the Okada40 scenario inundation area.

Table 2.6: Summary of number of buildings per construction type, for the new database and RiskScape database.

Construction summary (no. of buildings)		
Construction type	New database	RiskScape database
Light Timber	4228	5959
Concrete Masonry	414	723
Steel	20	17
Reinforced Concrete	37	541
Total	4699	7240

Table 2.7: Summary of number of buildings per use category, for the new database and RiskScape database.

Building purpose summary (no. of buildings)		
Building purpose	New database	RiskScape database
Residential	4361	7068
Commercial	173	103
Education	107	11
Community	27	10
Other	31	48
Total	4699	7240

There are large differences between the databases, with over 2500 more buildings contained within the RiskScape database than the new one. This is partly due to the presence of now-demolished buildings and small structures within the RiskScape inventory. Of particular note is the very large overestimation of the number of reinforced concrete structures compared to the new database, which would significantly skew the results of impact modelling due to the different fragility functions used.

A notable difference in the summary of building purpose is the under-representation of the number of commercial and educational buildings within the RiskScape database for this area. As these types of buildings are very important to the functioning of the community, this is a considerable shortcoming of the RiskScape database in this area.

2.3.4 Impact modelling

To estimate building damage due to tsunami inundation, impact modelling was undertaken. The modelling combined the newly created asset database with fragility functions to produce damage states per building. This was done using a combination of ArcMap and Excel, as the RiskScape software did not have the more recent fragility functions built in.

The impact modelling is essentially the same process employed by the RiskScape software, but with some differences. These include being able to model multiple runs at once, and produce disaggregated outputs.

Of the four tsunami inundation scenarios provided by NIWA, the Okada40 scenario is used for all impact modelling throughout this chapter. This is because it is one of the larger events which covers a significant portion of the built-up area of coastal Christchurch. It is also used to be consistent with the other two related Master's projects by James Williams and Lina Le, who are also primarily using the Okada40 scenario for their analysis. However, for comparison all four scenarios are used to produce some results, such as for a broad comparison of the number of buildings per damage state.

The fragility functions used are those developed by Suppasri et al. (2013). These were chosen due to the large dataset from which they are empirically derived (> 250,000 buildings, surveyed following the Great East Japan tsunami), and because the Japanese building stock is similar to that within New Zealand, compared to fragility functions developed based on tsunami impacting less developed countries (Fraser et al., 2014). There are separate fragility functions for four different construction types, and also for number of storeys for wood (light timber) and reinforced concrete buildings.

The Suppasri et al. (2013) fragility functions are for:

- Wood 1, 2, and 3 storeys or above
- Reinforced Concrete 1, 2, and 3 storeys or above
- Concrete masonry
- Steel

The fragility functions are used for estimating the probability of reaching different damage states, described in Table 2.8. The steps used for modelling the impacts to buildings are outlined in Figure 2.13.

Table 2.8: Damage state classification and description used for impact modelling. Table adapted from *Suppasri et al. (2013)*.

Damage state	Classification	Description	Condition
0	No damage	No damage to building	Possible to use immediately
1	Minor damage	There is no significant structural or non-structural damage, possibly only minor flooding	Possible to be use immediately after minor floor and wall clean-up
2	Moderate damage	Slight damage to non-structural components	Possible to be use after moderate reparation
3	Major damage	Heavy damage to some walls but no damage to columns	Possible to be use after major reparation
4	Complete damage	Heavy damages to several walls and some columns	Possible to be use after a complete reparation and retrofitting
5	Collapsed	Destructive damage to walls (more than half of wall density) and several columns (bent or destroyed)	Loss of functionality (system collapse). Non-repairable or great cost for retrofitting
6	Washed away	Washed away, only foundations remain; totally overturned	Non-repairable, requires total reconstruction

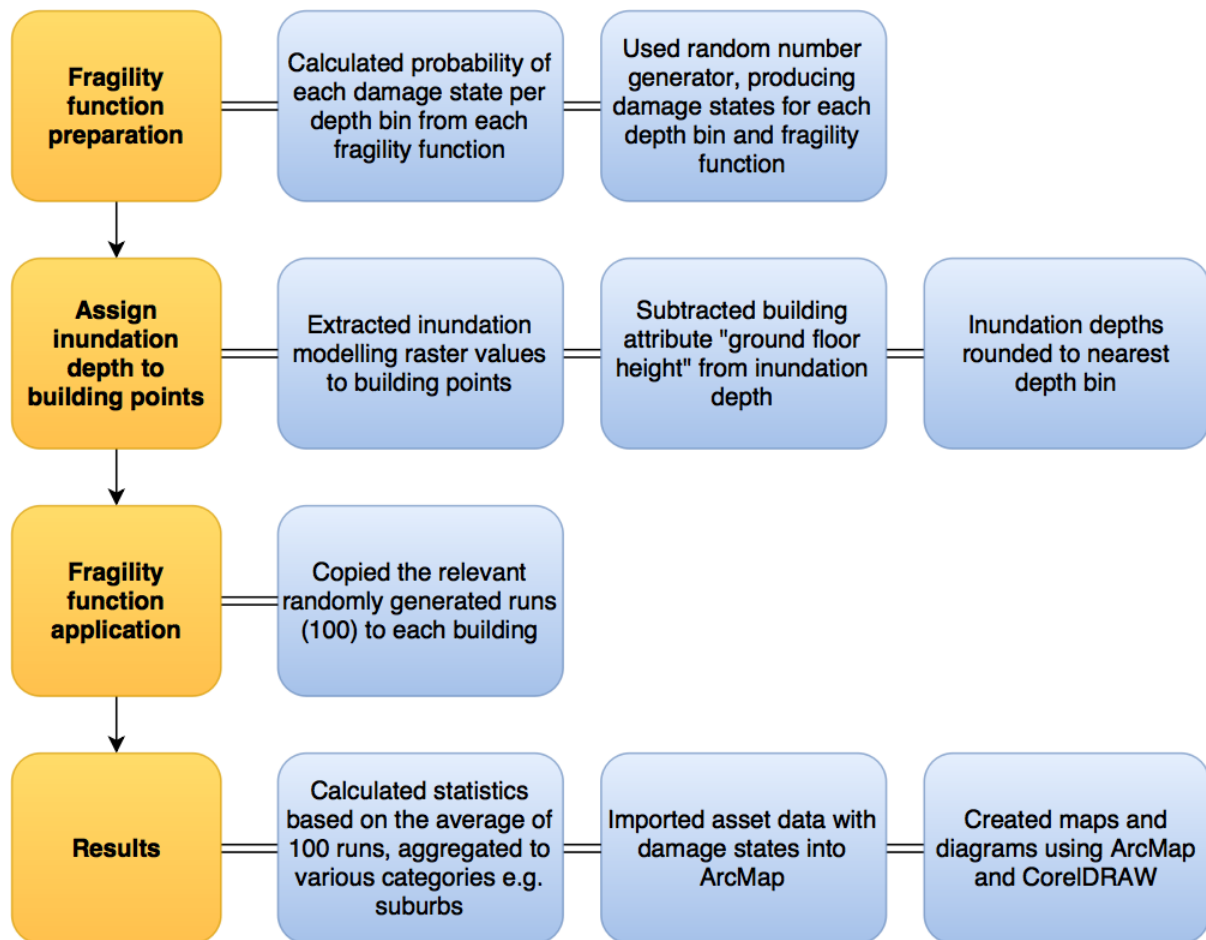


Figure 2.13: Outline of the process used for impact modelling and producing results from the outputs.

The first step was preparing the fragility functions in an appropriate format. The fragility functions were provided by Dr. Nick Horspool (GNS Science) in the form of an Excel spreadsheet containing the data used to make curves of the probability of reaching each damage state, for each water depth and construction type. The data were organised into depth bins, beginning at every 0.1 m up to 0.5 m, and every 0.25 m after that, up to 5 m (the maximum inundation depth on land, within the urban area). Because the probabilities of reaching each subsequent damage state were presented as cumulative, it was necessary to calculate the probability of each damage state within each depth bin.

Once this was complete, the random number generator (part of the “Data Analysis” tool in Excel) was used to generate damage states. The distribution of the random number generator was set to “Discrete”, which produces results based on the probability of any

value occurring (in this case, each damage state per depth bin, for each construction type). 100 runs of the random number generator were produced, and this was repeated 1000 times per depth bin. Therefore, the 100 runs are damage states, which may be applied to up to 1000 buildings (each building will have a different set of results). It was chosen to do 100 runs to provide a significant sample size for which to calculate statistics. Greater than 100 runs will produce slightly more refined results, however the processing time for modelling increases substantially.

The second step of the process involved assigning a depth value to each building. This was done by extracting the raster value of the inundation depth modelling to each building point. The ground floor height was then subtracted from this value, as higher structures may be less susceptible to damage from a given water depth (this assumption does not account for the effect of buoyancy, which may increase building damage if water is able to flow beneath the ground floor of a building). The resulting depth value is then rounded to the nearest depth bin.

The third step involves copying the results of the 100 runs to each building. The asset data are sorted by construction type, number of storeys and depth bin. The number of buildings within each category is then counted, and the appropriate number of results are copied from spreadsheets containing the randomly generated damage states. For example, if there are 250 single-storey wooden buildings within the 0.5 m depth bin, then the first 250 (out of 1000) sets of 100 runs are copied next to those buildings. For each category, the same runs are used regardless of the scenario they are applied to, providing comparable results.

Once all of the buildings for a scenario have been matched with damage states, statistics are calculated. These are done by considering all 100 runs (e.g. taking the average). The statistics are aggregated to various categories, e.g. suburbs or building purpose, depending on the intended format.

The results are also imported into ArcMap, where maps of various types are produced for different purposes. CorelDRAW was used for some maps and diagrams, using data imported from ArcMap.

An alternative method of impact modelling was also undertaken, in which the output is the probability of each building being in a certain damage state. This form of modelling does not involve randomly generated runs, and instead simply requires the relevant fragility function damage state probabilities to be copied to each building. It allows for the creation of maps that complement the results produced by the former method of modelling.

2.4 Results

This section presents the results of the impact assessment modelling for building damage due to tsunami inundation. The data are presented in a variety of forms, including tables and maps, which may be used for different purposes. This section fulfils the thesis objective of producing resources for emergency management planning and scenario exercising.

2.4.1 Number of buildings per damage state and comparison of scenarios

Statistics were calculated to show the number of buildings per damage state, and to examine the difference between inundation modelling scenarios.

The number of buildings per damage state for each of the four scenarios (see page 11) is shown in Table 2.9. The number of buildings between DS0 (no damage) and DS2 (moderate damage) is fairly similar across scenarios, except for Okada25B having a lower number of undamaged buildings. The results start to differ significantly for the higher damage states. Okada40 and Okada25A are the scenarios which have considerably more buildings with at least major damage. Okada30 is the least damaging scenario, followed by Okada25B.

The number of buildings within the inundation zone for each scenario, categorised by building purpose are shown in Table 2.10. The lower number of significantly damaged buildings in the Okada30 and Okada25B scenarios can be partially explained by the lower number of buildings present within the inundation zone. Overall, the number of buildings

within each inundation zone is very similar across building purpose categories, except for residential dwellings.

As each of the four scenarios represents an event with a 2,500 year return interval from the same source location, these results show how the source earthquake characteristics can have a significant influence on the inundation and impact modelling.

Table 2.9: Number of buildings per damage state for each scenario.

Number of buildings per damage state					
Damage State	Statistic	Scenario			
		Okada40	Okada30	Okada25A	Okada25B
DS0 – No damage	Min	1049	1147	1139	925
	Mean	1090	1186	1177	958
	Max	1142	1234	1225	1008
DS1 – Minor	Min	455	509	425	428
	Mean	507	556	472	475
	Max	549	598	510	508
DS2 – Moderate	Min	898	893	814	838
	Mean	958	948	875	904
	Max	1017	1014	955	965
DS3 – Major	Min	945	705	899	854
	Mean	1000	766	974	920
	Max	1090	822	1041	1007
DS4 – Complete	Min	169	68	202	140
	Mean	203	101	233	167
	Max	238	127	269	198
DS5 – Collapsed	Min	431	202	491	347
	Mean	469	234	528	382
	Max	506	266	574	424
DS6 – Washed away	Min	432	127	532	277
	Mean	474	153	581	322
	Max	520	174	614	360

Table 2.10: The number of buildings per use category within the inundation zone of each scenario.

Number of buildings within inundation zone				
Use Category	Scenario			
	Okada40	Okada30	Okada25A	Okada25B
Commercial	174	162	175	161
Residential	4361	3641	4502	3814
Industrial	12	10	13	10
Emergency Services	5	4	5	4
Community	27	24	28	27
Education	107	92	105	100
Religious	6	6	6	6
Other	7	6	6	6
Total	4699	3945	4840	4128

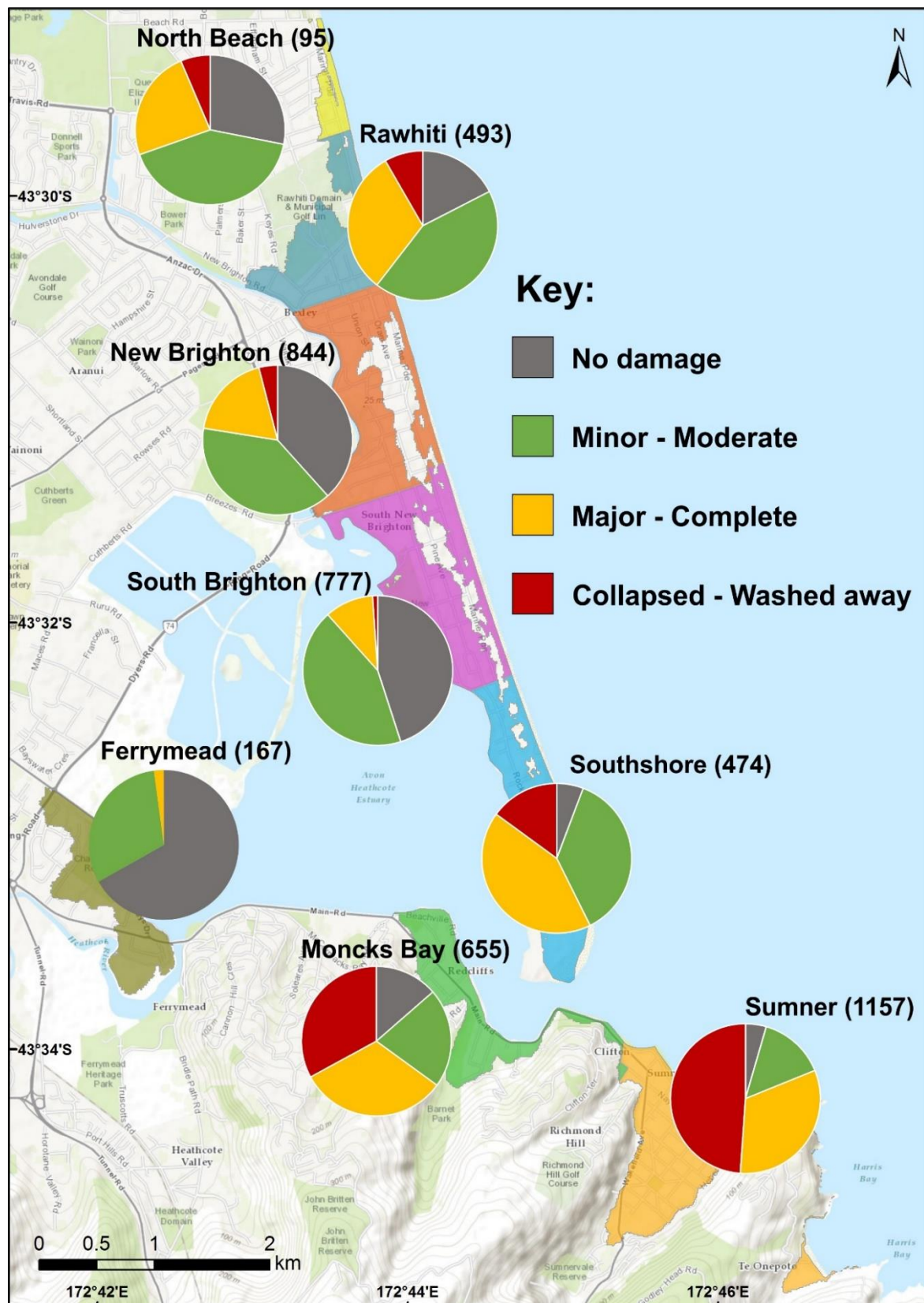


Figure 2.14: Map showing the proportion of buildings grouped into damage states for suburbs within the inundation zone (clipped to the Okada40 scenario, and coloured for differentiation). The total number of buildings within the suburbs is in parentheses. Some suburbs with very few buildings impacted (e.g. Mt Pleasant, Bexley) are not shown on this map.

The damage state results can be displayed visually in multiple ways. Figure 2.14 shows the proportion of buildings grouped into damage state categories, for suburbs within the Okada40 inundation zone. This map is intended to quickly show the relative severity of impacts. The data used are presented in Table 2.11, which also shows additional mildly impacted suburbs and the overall damage state proportions. Moncks Bay and Sumner are the most severely impacted, with over 50% of buildings reaching DS4 (complete damage) or above. Southshore is also significantly affected, with only 15% of buildings having less than moderate damage (DS2). Ferrymead is only lightly affected, with most buildings (67%) sustaining no damage, reflecting the shallow inundation depths within the suburb.

Table 2.11: The percentage of buildings (all use categories) per damage state, separated by suburb (based on the mean of 100 impact model runs).

Impact on buildings per suburb								
Suburb	No. of buildings	Percentage of buildings per damage state (Okada40)						
		DS0	DS1	DS2	DS3	DS4	DS5	DS6
Bexley	4	18%	20%	44%	17%	0%	1%	1%
Ferrymead	167	67%	16%	15%	2%	0%	0%	0%
Moncks Bay	655	14%	6%	15%	25%	7%	16%	17%
Mt Pleasant	32	70%	16%	10%	3%	0%	0%	0%
New Brighton	844	38%	15%	24%	17%	1%	3%	1%
North Beach	95	28%	15%	27%	22%	2%	5%	2%
Rawhiti	493	17%	13%	30%	29%	2%	6%	2%
South Brighton	777	45%	19%	24%	10%	0%	1%	0%
Southshore	474	6%	9%	28%	38%	4%	10%	5%
Sumner	1157	4%	3%	11%	22%	10%	21%	28%
Waimairi Beach	1	27%	35%	38%	0%	0%	0%	0%
Total	4699	23%	11%	20%	21%	4%	10%	10%

The disaggregated results can also be mapped. Figure 2.15 is a map of Redcliffs, displaying the distribution of damage states per building. This map only shows a single run of the impact assessment modelling for the Okada40 scenario, and therefore if another run were mapped the distribution could be significantly different. Examples of different runs

mapped for the same area are provided within Appendix B. This style of displaying data is useful for visualising the results from running the impact assessment model, but should not be used for considering the likely impacts to any individual building.

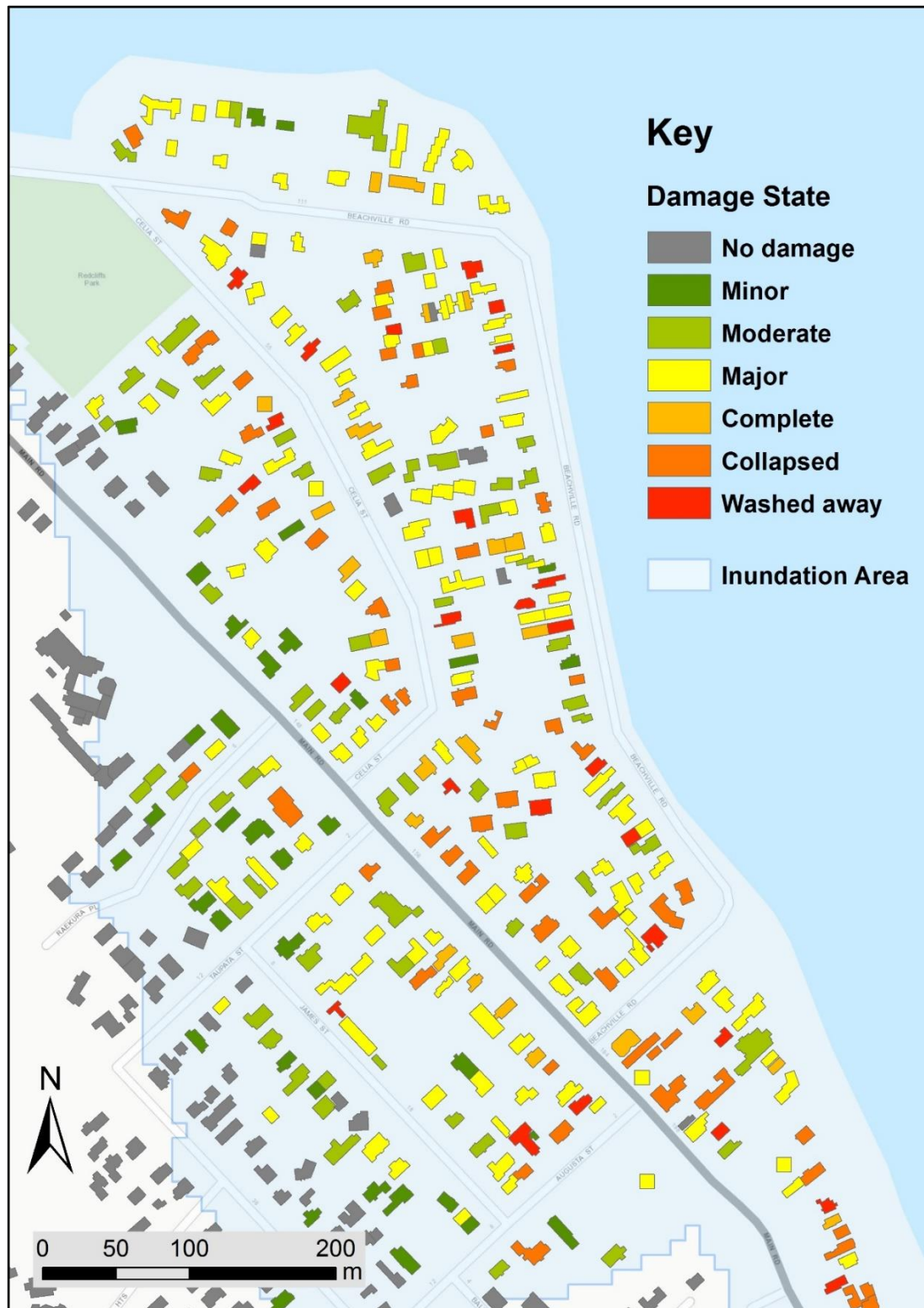
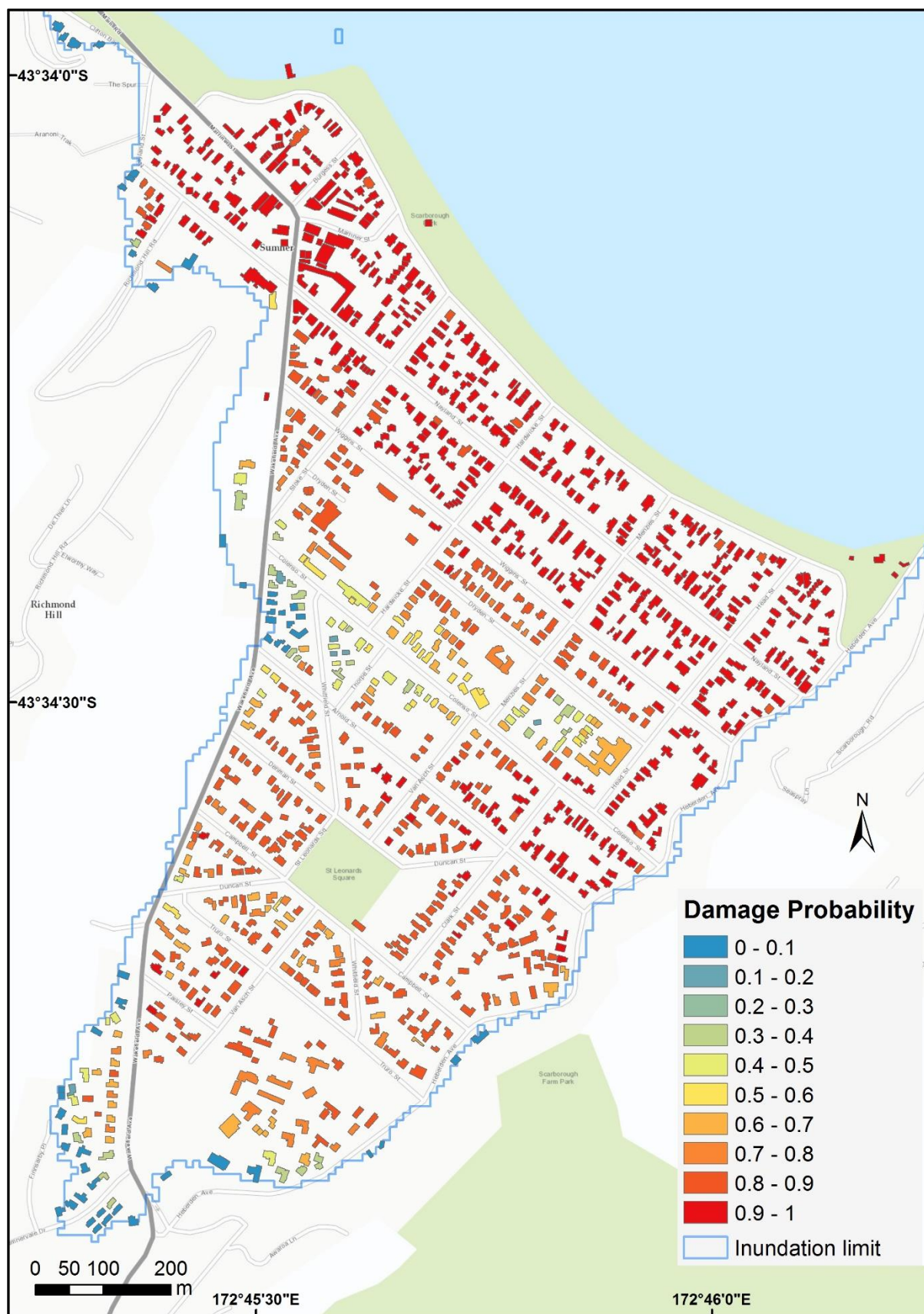


Figure 2.15: Example map of Redcliffs showing the damage state distribution of a single run of the impact assessment modelling for the Okada40 scenario.

2.4.2 Probability of damage state

The alternative impact modelling technique of applying the probability of damage states to each building was used to produce maps. These show the probability of reaching or exceeding certain damage states. Figure 2.16 shows the probability of each building in Sumner reaching or exceeding DS3 (major damage, and Figure 2.17 shows the probability of being at least DS5 (collapse). Apparent on both maps is that the probability of higher damage states reduces further from the coastline. Within the centre of the maps is an area of lower damage probability, caused by the presence of a paleo-dune which is an area of slightly higher elevation. The significant variation of damage probabilities in the north-west corner of Figure 2.17 is due to the large range of construction types within the commercial area of Sumner, and demonstrates the importance of accurate asset data in order to use the correct fragility function. The buildings of relatively low probability of collapse are multi-storey reinforced concrete, whereas those of higher collapse probability are mostly constructed of timber.

This method is most useful for displaying the potential damage distribution per building. It is comparable to maps showing the distribution of damage states (e.g. Figure 2.15), however it has the advantage that it contains all the probabilistic information and is not just a single realisation of a probabilistic process which can produce different results each time it is run.



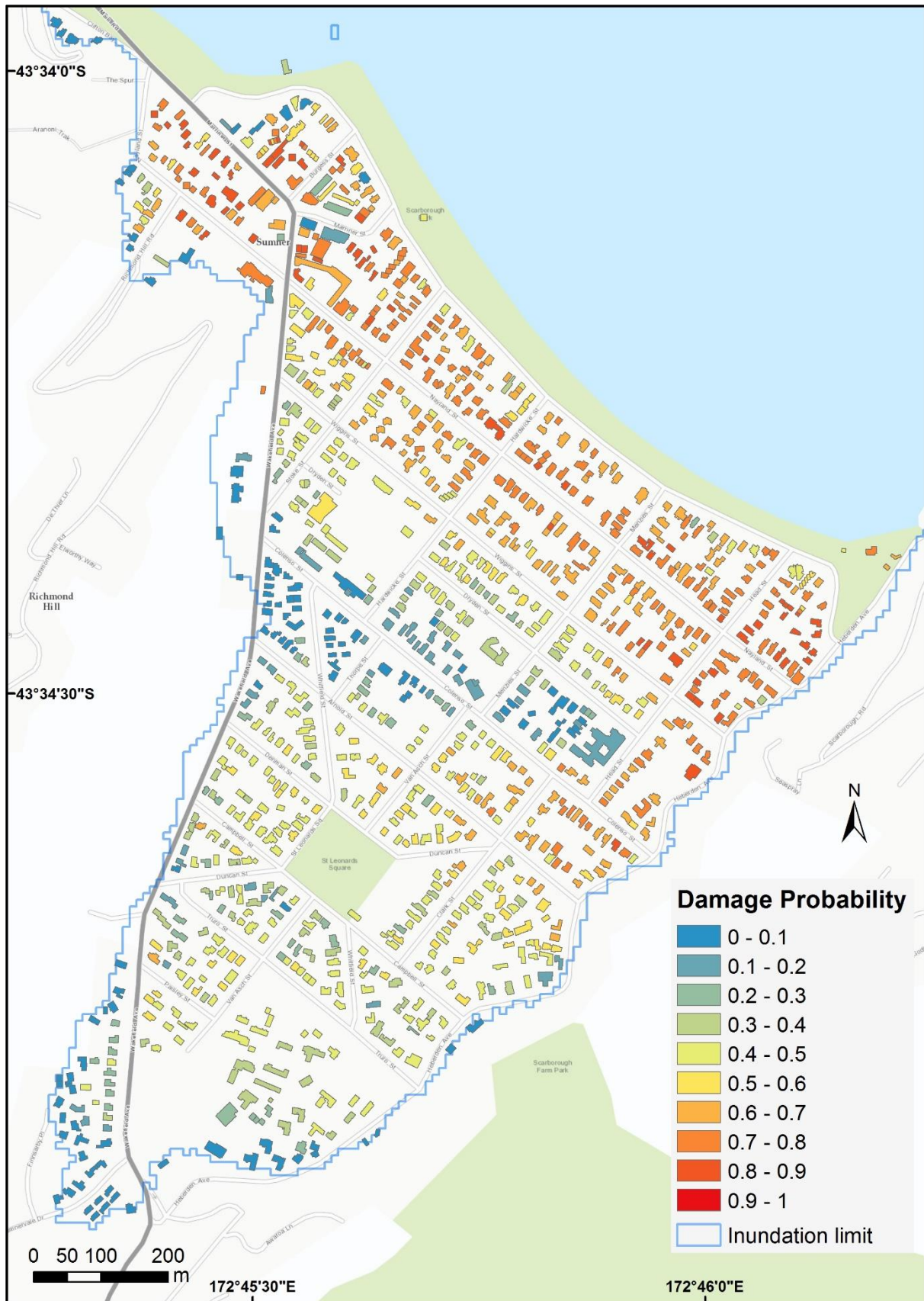


Figure 2.17: Map of Sumner showing the probability of each building reaching or exceeding DS5 (collapse), for the Okada40 scenario.

2.4.3 Population

The number of residential dwellings and population within the inundation zone for the Okada40 scenario are shown in Table 2.12. The population is the number of residences multiplied by the average number of people per household within the inundation zone (2.184, see page 48), rounded to the nearest whole number. This information may be used as a starting point to estimate the number of people that will need to be evacuated from each suburb.

Table 2.12: Number of residences and population within the inundation zone for the Okada40 scenario.

Population within inundation zone (Okada40)		
Suburb	No. of residences	Population
Bexley	4	9
Ferrymead	109	238
Moncks Bay	624	1363
Mt Pleasant	31	68
New Brighton	783	1710
North Beach	92	201
Rawhiti	431	941
South Brighton	758	1655
Southshore	474	1035
Sumner	1055	2304
Total	4361	9524

2.4.4 Impacts by building purpose

The percentage of buildings per damage state for the Okada40 scenario summarises the impacts for important building use categories. The impact on residential buildings (Table 2.13) is shown per suburb, and is very similar to the overall building summary shown in

Table 2.11 due to the prevalence of residential buildings within the inundation zone. The most severely impacted suburbs are Sumner and Moncks Bay, followed by Southshore, all with more than 50% of buildings sustaining at least major damage (DS3).

The impact on commercial buildings (Table 2.14) is shown only for the main commercial areas within the inundation zone. Sumner and Redcliffs (within Moncks Bay suburb designation) are particularly impacted, with over 95% of buildings sustaining at least moderate damage (DS2), and with a large proportion collapsed or washed away. The commercial buildings in New Brighton are slightly less damaged on average, with 66% suffering moderate or major damage. In all three suburbs, extensive repairs or reconstruction would need to take place before the commercial areas were functional again. Ferrymead is less severely impacted, with 95% of commercial buildings receiving only moderate damage or less.

The impact on schools (Table 2.15) within the inundation zone shows significant variation. Redcliffs and South New Brighton schools are not significantly affected and are likely to be functional soon after the event. All other schools sustain damage which is likely to disrupt normal operation for at least several months, most with over 80% of buildings receiving at least moderate damage. Particularly impacted are the schools in Sumner (Sumner Primary, Star of the Sea, Van Asch Deaf Education Centre) and Nova Montessori in New Brighton.

Table 2.13: The percentage of residential buildings per damage state, separated by suburb (based on the mean of 100 impact model runs).

Impact on residential buildings								
Suburb	No. of buildings	Percentage of buildings per damage state (Okada40)						
		DS0	DS1	DS2	DS3	DS4	DS5	DS6
Bexley	4	18%	20%	44%	17%	0%	1%	1%
Ferrymead	109	84%	10%	6%	1%	0%	0%	0%
Moncks Bay	624	13%	6%	16%	25%	7%	16%	17%
Mt Pleasant	31	69%	17%	11%	3%	0%	0%	0%
New Brighton	783	41%	16%	24%	15%	1%	2%	1%
North Beach	92	29%	15%	27%	22%	2%	4%	1%
Rawhiti	431	18%	14%	30%	28%	2%	6%	2%
South Brighton	758	44%	19%	25%	10%	0%	1%	0%
Southshore	474	6%	9%	28%	38%	4%	10%	5%
Sumner	1055	5%	3%	11%	22%	10%	21%	28%
Total	4361	24%	11%	20%	21%	4%	10%	10%

Table 2.14: The impact on commercial buildings within the inundation zone, displayed as percentage of buildings per damage state (based on the mean of 100 impact model runs). The four main commercial zones are separated out.

Impact on commercial buildings								
Suburb	No. of buildings	Percentage of buildings per damage state (Okada40)						
		DS0	DS1	DS2	DS3	DS4	DS5	DS6
New Brighton	64	3%	4%	25%	41%	10%	12%	5%
Sumner	30	1%	1%	4%	17%	19%	25%	34%
Redcliffs	16	1%	3%	15%	35%	13%	19%	13%
Ferrymead	47	34%	30%	30%	5%	0%	0%	0%
All	174	14%	12%	22%	24%	8%	11%	9%

Table 2.15: The impact on schools within the inundation zone, displayed as the percentage of buildings per damage state (based on the mean of 100 impact model runs).

Impact on schools								
School	No. of buildings	Percentage of buildings per damage state (Okada40)						
		DS0	DS1	DS2	DS3	DS4	DS5	DS6
Nova Montessori	5	4%	6%	31%	43%	2%	10%	5%
Central New Brighton	7	7%	11%	39%	36%	1%	5%	1%
New Brighton Catholic	8	7%	14%	42%	32%	1%	4%	1%
South New Brighton	12	91%	5%	4%	0%	0%	0%	0%
Redcliffs	4	100%	0%	0%	0%	0%	0%	0%
Sumner Primary	15	3%	4%	19%	35%	6%	17%	16%
Star Of The Sea	7	4%	6%	25%	37%	8%	14%	6%
Van Asch Deaf Education Centre	38	7%	6%	19%	32%	6%	17%	13%
All	96	20%	7%	21%	28%	4%	11%	8%

2.4.5 Comparison of database versions

Some of the residential buildings in the newly created database have attributes that were statistically extrapolated (see page 47); each time this is done the distribution of building attributes will be different. As this may influence the results of impact modelling, three different extrapolated asset databases were compared by modelling the impacts of the Okada40 scenario. The results of the number of buildings per damage state for each version are shown in Table 2.16, alongside the RiskScape database. The three created database versions show very little difference in results when used for impact modelling, and therefore the sensitivity to extrapolated residential building distribution is considered negligible. The RiskScape database has significantly more buildings within each damage category, especially DS0 (no damage) – DS4 (complete damage). This is a reflection of

greater number of buildings within the RiskScape database, as well as the different proportions of construction type.

Table 2.16: Comparison of number of buildings per damage state for three different extrapolated versions of the asset database (Ex. 1 – 3), as well as the RiskScape asset database.

Asset database comparison: Number of buildings (Okada40)					
Damage State	Statistic	Asset Database Version			
		Ex. 1	Ex. 2	Ex. 3	RiskScape
DS0 – No damage	Min	1049	1057	1058	1907
	Mean	1090	1095	1092	1971
	Max	1142	1147	1148	2050
DS1 – Minor	Min	455	458	462	812
	Mean	507	506	511	879
	Max	549	553	549	936
DS2 – Moderate	Min	898	892	896	1501
	Mean	958	960	957	1582
	Max	1017	1022	1021	1662
DS3 – Major	Min	945	934	937	1335
	Mean	1000	994	992	1399
	Max	1090	1079	1078	1487
DS4 – Complete	Min	169	169	172	246
	Mean	203	202	202	278
	Max	238	234	240	315
DS5 – Collapsed	Min	431	428	433	525
	Mean	469	466	471	565
	Max	506	505	510	610
DS6 – Washed away	Min	432	436	427	522
	Mean	474	477	475	566
	Max	520	514	515	608

2.5 Discussion

This section discusses the results, as well as the methodology used for creating the asset database and modelling the impacts. This includes using the RiACT application for field surveying, uncertainties and limitations of the methodology and results, and discussion of the RiskScape software.

2.5.1 The impact on communities

The impact assessment modelling produces results such as the number or proportion of buildings in a certain damage state, and may be categorised spatially and by building purpose. This forms the basis of how the impacts to communities can be considered. However, in order to consider the response and recovery measures required following a major tsunami event, it is important to consider how the communities function as a whole, with interrelated parts. For example, even if a residential area is relatively undamaged, if the schools and commercial buildings that serve the community are significantly impacted, the community will not function normally. There are also many important factors not directly related to building damage. As many of the issues relate to habitability and displacement of people, this is discussed further in Chapter 3.

2.5.2 Field surveying with the RiACT application

The RiACT application was used for most of the field surveying of buildings (see page 43). The software functioned adequately to enable the collection of building attribute data, however there were also many issues that made the process difficult.

Generally, the field surveying was a quick process, with each building able to be observed and attributes recorded in less than a minute on average. The speed with which surveying was able to be done was due to the fact that few attributes were needed to be collected, compared to the full range possible using the RiACT application. Although a building asset database containing many attributes is desirable, there is little purpose in collecting data on

attributes that are not used during impact assessment modelling, or used to describe the purpose of a building. For this project, it was preferable to have a large sample size of surveyed buildings. More than 1200 buildings were surveyed, which is a significant proportion of the total asset database created (6494 buildings), particularly within the inundation zones of each scenario (all less than 5000 buildings). Overall, the field surveying took around 20 – 25 hours across 6 separate days, with assistance from James Williams and Lina Le on some days reducing the amount of time in the field. It may be preferable for future building attribute field surveys to consider focusing only on the important and relevant attributes for collection.

There were several issues with the RiACT application that may need to be addressed:

- It was not possible to zoom in close enough to accurately place a building point within the centre of a footprint. This meant that all building points had to be checked in ArcMap and moved if necessary.
- A maximum of about 200 buildings was able to be surveyed at a time on any single device. This is because the application became extremely slow and unusable beyond this number.
- There was no easy way to only have the required attribute categories displayed in the list of possible entries, despite the ability to have customised templates within the application. This slowed the field surveying, as it was necessary to scroll through several categories to find the required attribute fields.
- The application is extremely demanding on battery life. This may be an issue with the devices used.
- RiACT did not work on the latest version of Android (5.x). This meant older devices that had not been updated had to be used, despite a new tablet being purchased by the Department of Geological Sciences, University of Canterbury for this purpose.
- Editing existing building points created duplicate entries, which is most likely a bug in the software. This meant that the building points could not be moved or altered without creating more issues, and if a mistake was made, building points had to be deleted and recorded again from the beginning.

As none of the field survey team were experienced in the construction of buildings or had access to properties for direct measurements, there is some inaccuracy and uncertainty within the field survey data. A field trip with Sheng-Lin Lin (GNS Science, developer of RiACT and an engineer) on 27th July, 2015 was undertaken to New Brighton to observe some buildings and develop the skills necessary to identify construction types within the inundation zone. This was of assistance particularly for commercial buildings, for which the construction type is commonly hard to identify. Most of the buildings surveyed within the created asset database are likely to have the main construction type correctly identified, especially as most buildings within the area are residential timber structures. However, there is always some uncertainty with attributes collected by non-experts.

The attributes of number of storeys and use category were straightforward to identify and record. However, the ground floor height had to be estimated by eye, from the distance of the street to the building. The measurements recorded for this attribute are therefore not precise, and depend on the perception of the surveyor.

2.5.3 Different methods of displaying data

There are multiple ways of displaying the outputs from the impact assessment modelling, including tables, graphs and maps. Each is useful for different purposes, but have caveats that must be considered, most of which are related to the impact assessment modelling process and data sources. Of particular note are disaggregated building impact or damage probability data. Maps showing individual buildings (e.g. Figure 2.15) should always be considered in the wider context of the locality, and not regarded as an accurate portrayal of what may happen to any given building. This is due both to uncertainties in the impact assessment modelling, such as the building attribute and inundation modelling data, as well as very localised features that may influence the impact to each building, for example the effect of shielding or debris. Aggregated results are less susceptible to these issues, and are less likely to be misinterpreted.

2.5.4 Uncertainties and limitations of impact assessment modelling

There are a number of uncertainties and limitations inherent to the impact assessment modelling. These include the accuracy of the inundation modelling, the asset database and fragility functions. This section describes some of the uncertainties and limitations, as well as how they may be addressed in future research.

2.5.4.1 Inundation modelling

The inundation modelling provided by NIWA (Lane et al., 2014) represents only four potential scenarios, all with the same 2,500 year return interval and source location. The inundation depths are also the result of the largest wave arriving at the time of Mean High Water Spring (MHWS). Therefore, the scenarios represent extreme tsunami events for Christchurch. This should be taken into account when considering the results, especially for emergency management planning, as tsunami events with a shorter recurrence interval which are more likely to occur within planning periods are likely to have significantly less impact. Additional impact assessment modelling, using inundation modelling from smaller tsunami events with shorter return intervals, would be valuable for comparing the difference between extreme events and those that are more likely to be experienced.

There are also limitations to the inundation modelling itself, as there are several factors influencing inundation depth and velocity that are simplified or not explicitly included in the modelling. In particular, the effect of erosion and drag from topographic features and buildings may alter the onshore wave propagation (Lane et al., 2014). The characteristics of the tsunami source are also very important, as demonstrated by the variation in scenarios (see page 11 and Appendix A). The modelling should therefore only be considered an approximation of what may occur in the event of a major tsunami, and some areas that are not inundated in the modelled scenarios may receive inundation and vice versa.

2.5.4.2 Asset database

Although all practical steps were taken to ensure the building asset database was as accurate as possible, there is still uncertainty in many aspects. The building locations are fairly accurate at the time they were examined using Google Earth imagery (dated 9/1/2015), however there will have been further demolitions and construction since that date. There also may be some buildings either included or deleted which are sheds or garages, due to the uncertainty with identifying building types using relatively low resolution imagery. There is some uncertainty with the field survey data, as previously discussed. The extrapolation of attributes to non-surveyed buildings is also an approximation of the true building stock within the database.

2.5.4.3 Fragility functions

The fragility functions used, from Suppasri et al. (2013), are based on the largest empirical dataset collected following a tsunami event, and are for buildings relatively similar to New Zealand's building stock. However, the differences between the building stocks of each country are uncertain, in terms of the potential for tsunami damage.

There are many factors leading to building damage that are not explicitly considered in the impact assessment modelling using fragility functions. The fragility functions, being created from empirical data, do implicitly include factors such as debris impact and shielding. For future impact modelling it may be preferable to consider these factors separately if time and resources allow. However, for some factors such as debris it would be necessary to model many scenarios to cover the possible eventualities, which may not result in a more certain outcome.

There are also issues with the statistical methods used to create the fragility functions, in particular the very uneven aggregation of surveyed data into bins, which may have led to an unrealistically rapid rise in curves for the lower damage states (Tarbotton et al., 2015).

2.5.4.4 Other factors

The number of runs used for the damage state modelling may have a slight influence on the robustness of results. 100 runs were used, as this was considered sufficient for the purposes of this project, and to reduce the processing time required to randomly generate the numbers. It would be preferable to have more runs (e.g. 10,000+), however this would have been difficult and time consuming to achieve, given the manual approach (within Excel) to the impact assessment modelling used here.

The assumption made of subtracting the ground floor height from the inundation depth does not account for the fact that some buildings may experience increased damage due the effect of buoyancy. The decision to incorporate this approach was following discussion with Dr. Nick Horspool (GNS Science).

2.5.5 RiskScape software

The RiskScape software was originally intended to be used for this project, either as the primary impact modelling program or for comparison with the process used. Some of the main reasons for not using the RiskScape software, and instead modelling the impacts using Excel and ArcMap are as follows:

- The RiskScape software does not currently have fragility functions built in. Instead, tsunami impacts are currently assessed using damage functions developed using data collected in Java and Samoa (Reese et al., 2011, 2007). The damage functions were created from surveys of buildings which are significantly different from those found in New Zealand. The fragility functions developed by Suppasri et al. (2013) are intended to be incorporated in the future.
- RiskScape does not currently allow export of disaggregated results, limiting flexibility in interpreting and displaying results. The outputs from RiskScape can currently only be exported to certain aggregation blocks within the software, such as suburbs, meshblocks or a 1 x 1 km grid.
- Only one run of the model is possible at a time. It is necessary to be able to specify the number of runs, as each run produces significantly different results.

- There is a general lack of transparency with the modelling process used by RiskScape. This is despite some documentation being provided online for certain aspects of the modules used. It is vital to fully understand the inputs and processes that lead to the outputs, for interpreting and displaying the results.

2.5.6 Summary

This chapter meets the primary objective of assessing the impact to buildings from a major far-field tsunami scenario, with robust results using an accurate and up-to-date building asset database and the most appropriate fragility functions currently available. This study demonstrates how fragility functions may be applied for tsunami impact assessments, in combination with a building asset database created using GIS methods and field surveying to obtain the relevant attributes. Although the RiskScape software was not used for the impact modelling, the methodology used for this study may contribute to the improvement of the software, for tsunami impact assessment modelling as well as for other natural hazards. The data is presented in multiple ways, which provides several resources for emergency management planning and scenario exercising.

Chapter 3: Assessment of building habitability and human displacement

3.1 Introduction

The first week following a tsunami event which has caused widespread damage to inhabited structures creates considerable demands on emergency management, with potentially large numbers of residents displaced and requiring emergency housing and welfare assistance. Impact and risk assessments can inform emergency management planning for this scenario by a) estimating likely damage to inhabited structures (as addressed in Chapter 2); and b) estimating the habitability of damaged housing in the affected area, including the timeframe for reoccupation of housing and the number of displaced residents. Habitability of housing in the aftermath of a damaging tsunami event is a complex issue, as safe occupation of damaged buildings is influenced by a range of factors, such as: extent and severity of direct tsunami damage to the buildings; access to essential services (e.g. electricity, water supply, sewage, transport networks); public health factors (e.g. ruptured sewer line, psychosocial impacts); casualty rescue and recovery; and access to alternative housing (Comerio, 1997; Jha and Duyne, 2010; Peacock et al., 2007; Power, 2013a; Wright et al., 2012). Access and return decisions may also be influenced by residents' and authorities' perception of acceptable risk.

This chapter addresses the broad issue of habitability of tsunami-damaged housing by reviewing available knowledge on the topic, and using this to inform development of a methodology for estimating building habitability and displacement of residents both spatially and temporally, using GIS software. The impact modelling of building damage (Chapter 2) is used in combination with additional data on potential factors influencing post-event habitability (e.g. access, functioning of utilities). Specifically, the main objective of this part of the thesis is to assess potential building habitability and displacement of people within the first week following the tsunami event, as requested by Canterbury CDEM.

3.2 Literature review

A literature review was conducted to examine studies that consider human displacement or building habitability following a major disaster. Of particular interest are the factors influencing building habitability and human displacement, and studies which have modelled human displacement following natural disasters. The focus was on studies considering events with similarities to tsunami (e.g. flooding), as well as contexts similar to Christchurch. As there are relatively few published studies with relevant information, a series of interviews were also conducted to provide additional information to inform the modelling process. The literature review and interviews form part of the risk identification step within the risk management framework.

3.2.1 Factors influencing building habitability and human displacement

The factors that contribute to whether a residential dwelling is habitable or uninhabitable following a tsunami event include the direct impacts of the event on buildings (see page 15) and infrastructure, and also the indirect and intangible factors that influence whether residents will want to return to their homes. A summary of the most important factors is provided in Table 3.1. The main factors considered are based on common themes throughout the examined literature, as well as the interviews (see section 3.2.3, page 83).

Table 3.1: The main factors identified as contributing to whether a building is determined as habitable, and whether residents are willing to return. Sources: *Comerio (1997); Jha and Duyne (2010); Peacock et al. (2007); Power (2013); Wright et al. (2012).*

Direct	Indirect	Intangible
Access – evacuation zone, debris, road damage	Closure or relocation of schools	Security / perception of safety
Damage to structure and contents	Economics e.g. increased costs, business disruption	Community functionality
Disruption to utilities e.g. power, water, wastewater	Workplace/income disruption	Public services disruption
Contamination	Insurance	Psychosocial factors

3.2.1.1 Direct factors

The direct factors include access, building damage, the functionality of utilities, and the potential for contamination from damaged sewerage systems (Jha and Duyne, 2010; Peacock et al., 2007; Power, 2013a; Wright et al., 2012). These are the most easily measurable aspects contributing to habitability, and may be assessed using GIS. They are particularly important within the first week following the event, however there is little published literature available with sufficient detail (e.g. specific short-term timeframes before restoration of access or utilities) to directly inform the GIS process.

Access to areas within the inundation zone following a tsunami event is limited due to a declared evacuation zone (as determined by authorities), potential road or bridge damage, and debris blocking access routes (Christchurch Engineering Lifelines Group, 1997; Francis and Yeh, 2006; Power, 2013a). The timeframe before authorities allow access for residents following evacuation is dependent on the risk of tsunami inundation having reduced sufficiently, and the safety of access routes. Roads and bridges may be damaged due to scouring, debris impact, sediment deposition and current velocity (Francis and Yeh, 2006; Nakanishi et al., 2014; Unjoh, 2012). Following the 2011 GEJT, essential road networks were restored rapidly, particularly for allowing access for response and recovery operations (Nakanishi et al., 2014). Specific details on recovery timeframes were not provided in Nakanishi et al. (2014). Disruption of access is one of the most significant impacts for community functionality, as experienced following the CES (Seville et al., 2014).

Disruption to utility infrastructure affects the habitability of buildings as well as the functioning of the community. Loss of power is frequently cited as having the greatest impact (Chang et al., 2007, 1996; Wright and Johnston, 2010). For households, the impacts of power loss are variable, depending on the availability of alternatives, e.g. heating and cooking facilities (Wright and Johnston, 2010). Electricity is integral to the functioning of many sectors within communities, including businesses, schools, and telecommunications, and therefore the disruption of power has a significant impact on household and community habitability. The disruption of water supplies impacts households in terms of consumption, hygiene, and other uses (e.g. lawn watering, car washing; Beban et al., 2013). Water supplies are also essential for many businesses and facilities within the community,

such as food outlets and medical centres (Buxton et al., 2014). Alternative supplies are possible if the primary infrastructure is disabled, such as from tankers providing drinking water (Beban et al., 2013). The loss of wastewater services may pose a hygiene hazard, especially if the wastewater infrastructure is damaged, as occurred during the CES where raw sewerage spilled from ruptured pipelines (Devane et al., 2014). The habitability of a building without waste disposal facilities is reduced, however alternatives may be provided (e.g. portable toilets). For all utilities, apartment blocks are more susceptible to disruption due to the lack of alternatives compared to free-standing houses (e.g. apartment blocks often require powered lifts, and free-standing properties enable the disposal of human waste on-site; Wright and Cousins, 2014).

Organisations that experienced loss of utilities following the CES suffered significantly reduced productivity compared to those that did not (Seville et al., 2014). The loss of electricity and water were the most disruptive, followed by wastewater. The loss of utilities increased the likelihood that an organisation would close, and customers were less likely to use an organisation's services (Seville et al., 2015, 2014).

There are interdependencies between utilities that may compound impacts and influence recovery times (Chang et al., 2007; McDaniels et al., 2007; Miles and Chang, 2006). For example, wastewater systems that need power to operate pumping stations will require the electricity network to be repaired first, which also requires road access. The recovery times for infrastructure are highly contextual, due to the great variation in systems in different localities, and the differing exposure to hazards such as tsunami.

3.2.1.2 Indirect and intangible factors

The indirect and intangible factors (Table 3.1) include the functioning of the community (schools, local businesses, workplaces, public services), psychosocial factors (e.g. stress) and the sense of security or perception of ongoing risk (Comerio, 1997; Jha and Duyne, 2010; Peacock et al., 2007; Power, 2013a; Wright et al., 2012). These factors are more difficult to assess using GIS or other models, typically requiring specific data and approaches (e.g. economic impact modelling).

Levine et al. (2007) examined the literature relating to displacement of people and the decisions to return or relocate following major disasters. A general lack of research into the topic is noted. However, that which exists is often focused on ethnic or socioeconomic factors that are only relevant to the particular localities studied. Of relevance is the tendency for people to return to their homes if they have good relations with their neighbours; if they live in tight-knit communities; or have access to their own vehicle. Residents with young children were less likely to return to an area perceived as unsafe.

An important factor that is directly related to the restoration of a residential dwelling following tsunami or flooding damage is the time required to clean up before a building is habitable. This situation assumes little or no structural damage. There is no literature available that specifically addresses this topic for a tsunami affecting a developed country (e.g. Japan). A search was conducted of clean up times for flooding, however there was no specific data found, with only anecdotal accounts available of the recovery process collected via interviews (e.g. Whittle et al., 2010), or general information on housing restoration following a flood (e.g. BRANZ, 2004).

3.2.1.3 Population movement

Studies into population movement in Christchurch following the CES focused on the medium- to long-term population changes. Statistics New Zealand (2012) used cellphone data to examine where people migrated to following the February 22, 2011 earthquake. The focus of this study was on the weeks up until April 30, 2011. The data showed which regions people migrated to, and timeframes before the return of residents to Christchurch. Data from New Zealand Post mail redirections and school enrolments have also been used to measure post-earthquake population changes (Canterbury Earthquake Recovery Authority, 2014). However, these studies do not have the accuracy necessary to describe or estimate very short-term population movements, for example where displaced residents specifically stayed within Christchurch and for how long.

Examples from other disasters also focus on longer-term population migration. Most events are not particularly well-studied, with very sparse data available. Notable exceptions include the 1995 Kobe earthquake in Japan (Horwich, 2000), and Hurricanes Andrew,

Katrina (Fussell et al., 2010; Hori and Schafer, 2010; Levine et al., 2007; Sastry, 2008) and Sandy (Abramson et al., 2015) in the United States. Love (2011) examined the literature available from some of these events and compared it to the Christchurch context. The most relevant conclusions were that migration and return of residents is strongly correlated with degree of damage to homes, including at a localised geographic level; displaced residents were likely to move only short distances if possible; and residents from low socioeconomic neighbourhoods are more likely to be displaced and for longer periods. Using data collected in Japan, Fujimi and Tatano (2012) concluded that residents typically have a very strong preference for returning to their home, as opposed to relocating. Unfortunately, none of the studies have detailed information on the displacement of people within the first week following an event, except in the case of evacuation (e.g. Abramson et al., 2015; Fraser et al., 2012). The information available on reasons for residents returning to their homes is typically within the context of long-term recovery.

3.2.2 Modelling human displacement

There are a few examples of using modelling software to estimate displacement following damaging natural events, and all are partly based on residential building habitability. The timeframe of displacement for residents is an output of the RiskScape software (King and Bell, 2009), but is solely tied to the damage state of a building, which in itself is estimated using inaccurate methods (see page 34). The flood module within the HAZUS-MH software, which is modelling software similar to RiskScape developed for the United States context, has a function which estimates housing needs following a flood (Scawthorn et al., 2006). The factors considered are building damage, access and demographics (e.g. age, income), and the outputs are focused on short-term sheltering requirements as opposed to the habitability of existing buildings. No further details are provided on the methodology in Scawthorn et al. (2006).

The number of evacuated residents following a large Hikurangi Subduction Zone earthquake generating a tsunami impacting the Wellington Region was modelled by Wright and Cousins (2014). The modelling estimated the timeframe of displacement based on building damage from both the earthquake and tsunami, as well as tsunami zone evacuation

and restoration of drinking water services. Fragility functions were used to determine building damage due to the earthquake (from Spence et al., 2008), and damage ratios were used for tsunami impacts on buildings (source was not specified). Estimates of the number of people displaced and the timeframe before reoccupation also considered the type of building (e.g. stand-alone houses could be reoccupied sooner than apartments, due to less reliance on provision of services). The modelling is only relevant to the Wellington context, and is largely supported by qualitative discussion, noting the many assumptions and uncertainties in the results. The work expands upon similar modelling done by Wright et al. (2012) for an earthquake scenario affecting Wellington, that does not include a tsunami.

A model was created to estimate displacement following the September 4, 2010 earthquake in Canterbury by Giovinazzi et al. (2012), based on Earthquake Commission (EQC) data. The EQC provides insurance cover for natural hazard-induced disasters, and the data were collected by field surveyors assessing buildings for the degree of damage and to estimate repair requirements. The model also accounts for: increased housing demand by contractors and employees moving into the area for the rebuild; the response of agencies that may affect housing demand; and the behaviour of individuals when assessing their own needs. However, this type of modelling required data collected after the event had occurred, and was only able to estimate displacement at a broad area level. There are no specific details on how the model was developed and applied in Giovinazzi et al. (2012).

Other approaches for estimating the displacement of people were considered by Giovinazzi et al. (2012). The number of people requiring temporary housing was estimated by using building safety evaluation data provided by Christchurch City Council (CCC), which had information on whether buildings had red (unsafe to enter) or yellow (restricted use) tags. These evaluations were combined with demographic data to estimate the number of people requiring rehousing. Announcements about land zoning and the provision of utilities were also considered. A concept was theorised to create a “neighbourhood liveability index” using GIS data on schools businesses to indicate whether residents would want to return to an area, for those populations not displaced due to uninhabitable buildings. However, insufficient time and constraints on data provision prevented the index from being completed. Although the modelling by Giovinazzi et al. (2012) serves as a useful example, particularly for the Christchurch post-disaster context, the models rely

on data obtained following an event (ex post), whereas this chapter is focused on an ex ante assessment.

The various models assessing human displacement all contain many assumptions and uncertainties, and represent attempts to estimate displace populations and timeframes based on limited data.

3.2.3 Interviews

As there are few published studies regarding human displacement or building habitability following a tsunami, especially those that are applicable to the Christchurch context, a series of interviews and discussions were conducted, in order to provide some information to reduce the assumptions and uncertainty associated with the processes outlined. The discussions were mostly be informal, and are regarded as “expert opinions” which assisted in evaluating the relevant steps of the process. These were generally meetings involving people with knowledge of the project, e.g. emergency managers or people with specialised knowledge in a certain area. The interviews were semi-structured, and involved responding to a series of questions (Appendix D) aimed at addressing shortfalls in the literature. A Human Ethics Committee Low Risk application was approved for the interviews (Appendix D). The interviewees are required to remain anonymous as a condition of the Human Ethics approval.

Interview participants included first-responders to overseas tsunami events and those with recent experience of flooding and earthquakes in Christchurch. The main topics covered in the interviews included establishing the interviewee’s experience with natural hazards; the factors that make a building habitable or uninhabitable; the relative importance of utilities; the factors leading to residents’ decision to return to their homes; and how long it typically takes to clean up a lightly damaged residential dwelling following a tsunami or flooding event. The data were analysed by considering the main themes across the responses for each question, which were typically similar between interviewees. Additionally, points relevant to the local context were also specifically noted.

The main findings from the interviews were:

- The main factors affecting habitability and residents' decisions to return are: access; provision of utilities; safety; whether residents have alternative places to stay; fear of ongoing risk from tsunami; seasonal factors e.g. how warm the house is likely to be; and whether residents have insurance.
- Power is the most important utility, followed by water and wastewater which are roughly equal in importance.
- The clean-up time before reoccupation of flood-affected homes varies widely, and depends on the context. In developing countries, reoccupation was very fast, within 2 – 4 days for homes with minor damage. In developed countries, the timeframe may be 10 days or more, depending on inundation time. Exceptions to this were uninsured homeowners in Christchurch affected by the 2014 floods, who typically immediately reoccupied their homes due to a lack of finance to temporarily relocate.
- The normal functioning of the community is important for residents to decide to return, but ultimately the most important factor is the habitability of their home.
- Opinions were mixed on whether residents relied on official guidance or their own intuition and knowledge when deciding whether to return to their homes.
- Community links and assistance provided were essential in the recovery from events in both developed and developing countries.

The interviews and discussions provided an opportunity to fill in some gaps in the literature, and develop a stronger foundation with which to estimate the habitability of buildings and displacement of residents in the Christchurch context.

3.2.4 Summary

Many common themes were repeated throughout the literature, and supported by the interviews and discussions. The factors contributing to habitability are often similar across different contexts (e.g. developed versus developing countries, different hazard types), however specific information relevant to tsunami impacts and the Christchurch context is

generally lacking, especially for the first week following an event. These uncertainties of background information needs to be considered throughout the methodology and results.

As the impacts on infrastructure due to tsunami are highly contextual (depending on the systems present within a locality, their exposure to the tsunami hazard and their interdependencies), the impacts and timeframes for recovery for a given scenario need to be considered based on specific local knowledge. This may be informed by literature, experiences from past events and expert opinion. For Christchurch, the CES has highlighted many of the vulnerabilities of infrastructure to earthquakes, however the impacts from tsunami are likely to be very different. Therefore, estimating the potential impacts on infrastructure in Christchurch requires modelling or examination of a scenario based on expert opinion.

Previous studies which modelled habitability and displacement of residents generally did so based on limited data, and with a variety of techniques that are difficult to apply to a different context or scenario. Therefore, an aim of this chapter is to outline a methodology that can be used as a basis for further development of assessing habitability and displacement using GIS.

3.3 Methodology

3.3.1 Overview

Assessing the habitability of buildings and displacement of residents using GIS requires consideration of the local context and scenario, and the relative influence of contributing factors. It is not possible to incorporate all contributing factors into the GIS modelling due to complexity and currently sparse literature on the topic. Therefore the GIS modelling serves as a base assessment, which can then be used with further consideration of other factors during planning or exercising. This section of the chapter forms part of the risk analysis step of the risk management process.

The key steps involved in assessing building habitability and displacement of residents following a tsunami event are shown in Figure 3.1. The flow chart lists the information

sources used in each step, and the main assumptions that are made. The process outlined serves as an example of the methods that may be used for assessment of habitability or displacement using GIS, considering some of the primary measurable contributing factors. There are assumptions and uncertainties associated with each step, and these are described throughout the methodology section. The broad methodology may be applied to other contexts and scenarios, for tsunami as well as other natural hazards.

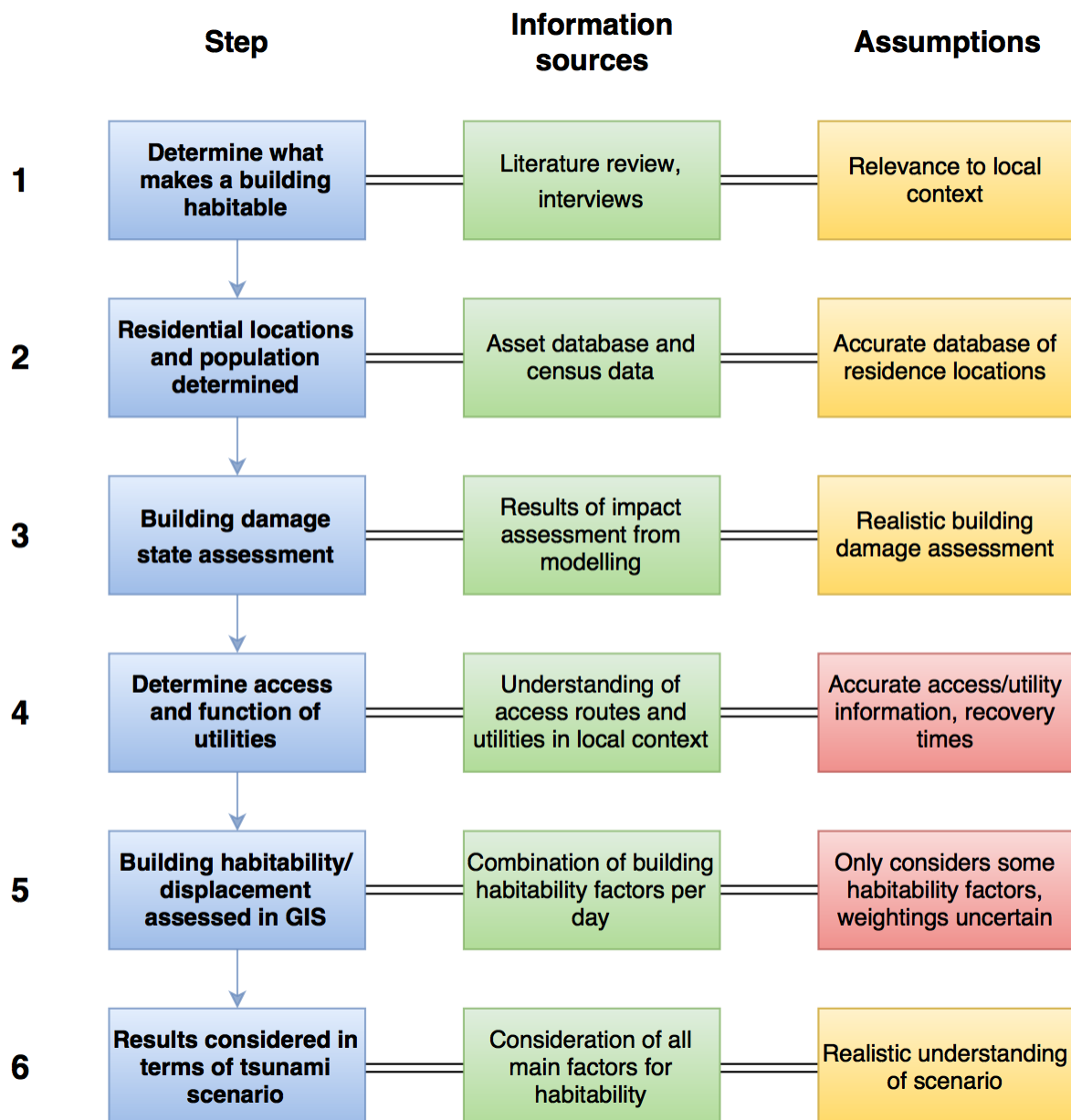


Figure 3.1: Overview of the methodology for assessing building habitability and the displacement of residents following a tsunami event. For each step of the process, the information sources and main assumptions are listed. The red boxes in the “Assumptions” column indicate the relatively high degree of uncertainty involved with those steps in the process.

3.3.2 Building and population data

A fundamental part of assessing residential habitability and displacement is collating a database of buildings and population within the hazard area. As building damage is an important contributing factor, this needs to be modelled as part of the process. A reasonable estimate of the population within the study area is required, which may be established using census data.

For this study, the results of the impact assessment modelling of tsunami damage to residential buildings for the Okada40 scenario are used (see page 55). The results used are single runs of the impact modelling, giving a distribution of residential buildings per damage state. Non-residential buildings are excluded, as the habitability assessment process is specifically targeted at residences. The population is the number of residential dwellings multiplied by the average number of occupants per household (2.184, see page 48 for calculation).

3.3.3 Access and functionality of utilities

The direct factors of access and functionality of utilities are important aspects of whether a building is regarded habitable, as noted in the literature and the interviews. These factors are tangible and vary spatially and temporally, and are suitable for incorporation into a habitability assessment using GIS. This is achieved by creating polygons in ArcMap across areas which do not have access or provision of each utility (power, water, wastewater), for each day following the tsunami event (up to 7 days). Therefore, the areas not covered by the polygons have the relevant utility or access available. The availability of each utility or access route can be determined for individual buildings. The polygons are created based on local knowledge of the infrastructure (including interdependencies), with the impacts and timeframe of restoration considered in terms of the scenario. The Okada40 inundation modelling and scenario were used to create the polygons, which are shown in Appendix C. Access was determined by consideration of the tsunami scenario, how various factors may influence which areas have access, and how long it may take before obstructions are cleared. For the first day of the tsunami event, it is assumed that all residents within the

inundation zone are evacuated, and will not be allowed back into the inundation zone until there is no longer a significant hazard from tsunami inundation on land, approximately 24 hours after first wave arrival (Lane et al., 2014). The access on Days 2 & 3 is loosely based on areas of the most severe building damage, where it could be expected that large amounts of debris are covering access routes, especially from damaged buildings but also other materials such as trees and boats. The arterial routes into Redcliffs/Moncks Bay and Sumner are likely to be disrupted due to flooding and debris, however no bridges are expected to suffer significant damage (Christchurch Engineering Lifelines Group, 1997). The remaining areas of no access on Day 4 are where many buildings have collapsed, and therefore more clean-up is required due to debris. This includes the suburbs of Redcliffs/Moncks Bay and Sumner, which have particularly limited access due to reliance on the coastal road. The restoration of access throughout the inundation zone is likely to be fairly rapid, particularly as the expected damage to the road network is substantially less than that experienced in Japan following the 2011 GEJT, where restoration was achieved rapidly (Nakanishi et al., 2014). It is assumed that all routes are clear and access is restored everywhere by Day 5. Access is required before any utilities within the affected area can be restored.

The polygons of utility functionality were developed during an informal meeting with Karn Snyder-Bishop, Water and Wastewater Network Operations Engineer at Christchurch City Council, which took place on 17th November, 2015. Mr. Snyder-Bishop has extensive knowledge of the water, wastewater and power networks within Christchurch, and the interdependencies between them. He also has experience of how the infrastructure performed during the Canterbury earthquake sequence. It was necessary to create the polygons based on expert opinion and local knowledge, as the impacts to infrastructure and recovery timeframes are very contextual.

Power is likely to be out in most areas from Days 1 – 3, where damage to poles and transformers may have taken place. The exception is the area around Ferrymead, where low inundation depths are unlikely to disrupt power supply. Restoration is dependent on access, and may take 1 – 2 days once crews are able to enter the affected areas. The highly damaged areas of Moncks Bay and Sumner are unlikely to have power for more than one week, due to extensive damage and limited access.

The water supply is assumed to be severed throughout the inundation zone immediately following the tsunami arrival. Restoration is dependent on access, and the level of damage to the network is likely to correlate with the distribution of building damage, as pipes are broken when buildings are damaged. Some water supply is restored to areas of relatively low damage on Day 5, but many areas will have no mains water supply for 1 – 2 weeks.

Wastewater is also assumed to be unavailable throughout the inundation zone. The disposal of wastewater is dependent on power, but may be restored relatively quickly using generators once access is available. Wastewater is restored to areas of relatively low damage on Day 3, but remains unavailable in Moncks Bay and Sumner for at least one week, as there is little purpose in restoring wastewater when most buildings are destroyed or severely damaged. The restoration of wastewater assumes that significant amounts of silt have not entered the system, which is possible during tsunami inundation. If silt were present within pipes, it could take 2 – 3 weeks to restore functionality.

All of the resulting polygons were checked with James Thompson (Canterbury CDEM), Marion Gadsby (Environment Canterbury) and Emily Lane (NIWA) to verify their realism, based on expert opinion. However, there is a large degree of uncertainty with the polygons, due to the complexity of estimating how access and utilities are likely to function following a major tsunami.

3.3.4 Assessment in GIS

To determine the habitability of buildings in GIS, the contributing factors are given a weighted score that reflects their relative influence on habitability. The scores for each factor are added together to produce an overall tally per building. This is done for each day following the tsunami event, for the time period considered. The tallied scores for each building are then compared to a threshold score which determines whether a building is habitable or uninhabitable.

The factors and their weightings used in this assessment are shown in Table 3.2. The scores are tallied for each residential building within the inundation zone and for each of the first 7 days following the tsunami event. Each building is given a score if the building damage

fits one of the categories, or access or utilities are unavailable. A score of 10 or more is considered uninhabitable, and less than 10 is habitable.

Table 3.2: Factors considered in the GIS analysis of building habitability, and the weightings applied. A score is applied for access, power, water and wastewater if they are unavailable for a building.

Factor	Weighting
Access	10
Building damage: Minor (DS1)	5
Building damage: Moderate or greater (DS2 - DS6)	10
Power	3
Water	2
Wastewater	2

The weightings reflect the relative importance for residential building habitability and are based on the literature review and interviews. Access is essential for a building to be occupied, and therefore is given a score of 10 (uninhabitable). Buildings with minor damage (DS1) may be able to be occupied relatively quickly following clean-up (Suppasri et al., 2013a), and therefore have a score of 5. Buildings with moderate or greater damage will typically require repairs before reoccupation, which are likely to take at least a month, and therefore the score is 10 (uninhabitable). Power has a score of 3, compared to water and wastewater which have scores of 2, in recognition of the greater importance of power compared to the other utilities for habitability. However, all utilities are significantly less important than access or building damage.

All of the weightings are very rough estimates intended as a starting point for assessing habitability in GIS. These are likely to be inaccurate, and more research is needed to create realistic habitability factor weightings.

3.4 Results

The results of the habitability assessment are shown in Table 3.3, and the corresponding number of displaced residents is shown in Table 3.4. The results are broken down by suburb and each day for the first week following the tsunami event. The results per suburb include only the residential dwellings and population within the inundation zone, or completely surrounded by inundation for the suburbs of New Brighton, South Brighton and Southshore. The number of displaced residents is the number of uninhabitable buildings multiplied by the average number of occupants per household (2.184, see page 48 for calculation). Days 2 & 3, and Days 5 & 6 are the same due to the way restoration of access and utilities are closely linked.

Initially, all residences (5,016) are uninhabitable due to evacuation, with 10,955 people displaced. As access and utilities are restored, the number of displaced residents decreases across the week, with 6,253 requiring alternative accommodation on Day 7. Beyond the first week the displacement of residents is primarily due to building damage, with 6,176 people displaced from buildings with at least moderate damage, requiring at least a month before reoccupation is possible.

Table 3.3: Number of habitable or uninhabitable residences per suburb, for the first 7 days following the tsunami event.

Number of habitable or uninhabitable residences per suburb								
Suburb	Habitable	Day following tsunami event						
		1	2	3	4	5	6	7
Bexley	No	4	4	4	2	0	0	0
	Yes	0	0	0	2	4	4	4
Ferrymead	No	123	8	8	8	8	8	8
	Yes	0	115	115	115	115	115	115
Moncks Bay	No	633	632	632	577	548	548	513
	Yes	0	1	1	56	85	85	120
Mt Pleasant	No	31	4	4	4	4	4	4
	Yes	0	27	27	27	27	27	27
New Brighton	No	1141	544	544	448	318	318	318
	Yes	0	597	597	693	823	823	823
North Beach	No	103	94	94	70	51	51	51
	Yes	0	9	9	33	52	52	52
Rawhiti	No	482	455	455	349	287	287	287
	Yes	0	27	27	133	195	195	195
South Brighton	No	960	486	486	436	333	333	287
	Yes	0	474	474	524	627	627	673
Southshore	No	474	474	474	458	444	444	392
	Yes	0	0	0	16	30	30	82
Sumner	No	1065	1065	1065	1065	1003	1003	1003
	Yes	0	0	0	0	62	62	62
Total	No	5016	3766	3766	3417	2996	2996	2863
	Yes	0	1250	1250	1599	2020	2020	2153

Table 3.4: Number of displaced residents per suburb, for the first 7 days following the tsunami event. The number of residents is based on the average number of occupants per household within the inundation zone (2.18, see page 48 for calculation), rounded to the nearest whole number.

Number of displaced residents per suburb								
Suburb	Displaced	Day following tsunami event						
		1	2	3	4	5	6	7
Bexley	Yes	9	9	9	4	0	0	0
	No	0	0	0	4	9	9	9
Ferrymead	Yes	269	17	17	17	17	17	17
	No	0	251	251	251	251	251	251
Moncks Bay	Yes	1382	1380	1380	1260	1197	1197	1120
	No	0	2	2	122	186	186	262
Mt Pleasant	Yes	68	9	9	9	9	9	9
	No	0	59	59	59	59	59	59
New Brighton	Yes	2492	1188	1188	978	695	695	695
	No	0	1304	1304	1514	1797	1797	1797
North Beach	Yes	225	205	205	153	111	111	111
	No	0	20	20	72	114	114	114
Rawhiti	Yes	1053	994	994	762	627	627	627
	No	0	59	59	290	426	426	426
South Brighton	Yes	2097	1061	1061	952	727	727	627
	No	0	1035	1035	1144	1369	1369	1470
Southshore	Yes	1035	1035	1035	1000	970	970	856
	No	0	0	0	35	66	66	179
Sumner	Yes	2326	2326	2326	2326	2191	2191	2191
	No	0	0	0	0	135	135	135
Total	Yes	10955	8225	8225	7463	6543	6543	6253
	No	0	2730	2730	3492	4412	4412	4702

The proportion of displaced residents per suburb for different days of the week is shown in Figure 3.2. This figure gives a visual summary of how displacement (and corresponding building habitability) changes over time.

The number of residents displaced can also be displayed per census meshblock. Figure 3.3 shows the number of residents displaced for between 1 and 7 days, and excludes those displaced for longer. This map is useful for assessing those who may need short-term accommodation, and where they normally reside. Figure 3.4 shows the number of residents displaced for more than one week, and is a visualisation of the most severely affected areas, with displaced residents needing longer-term accommodation.

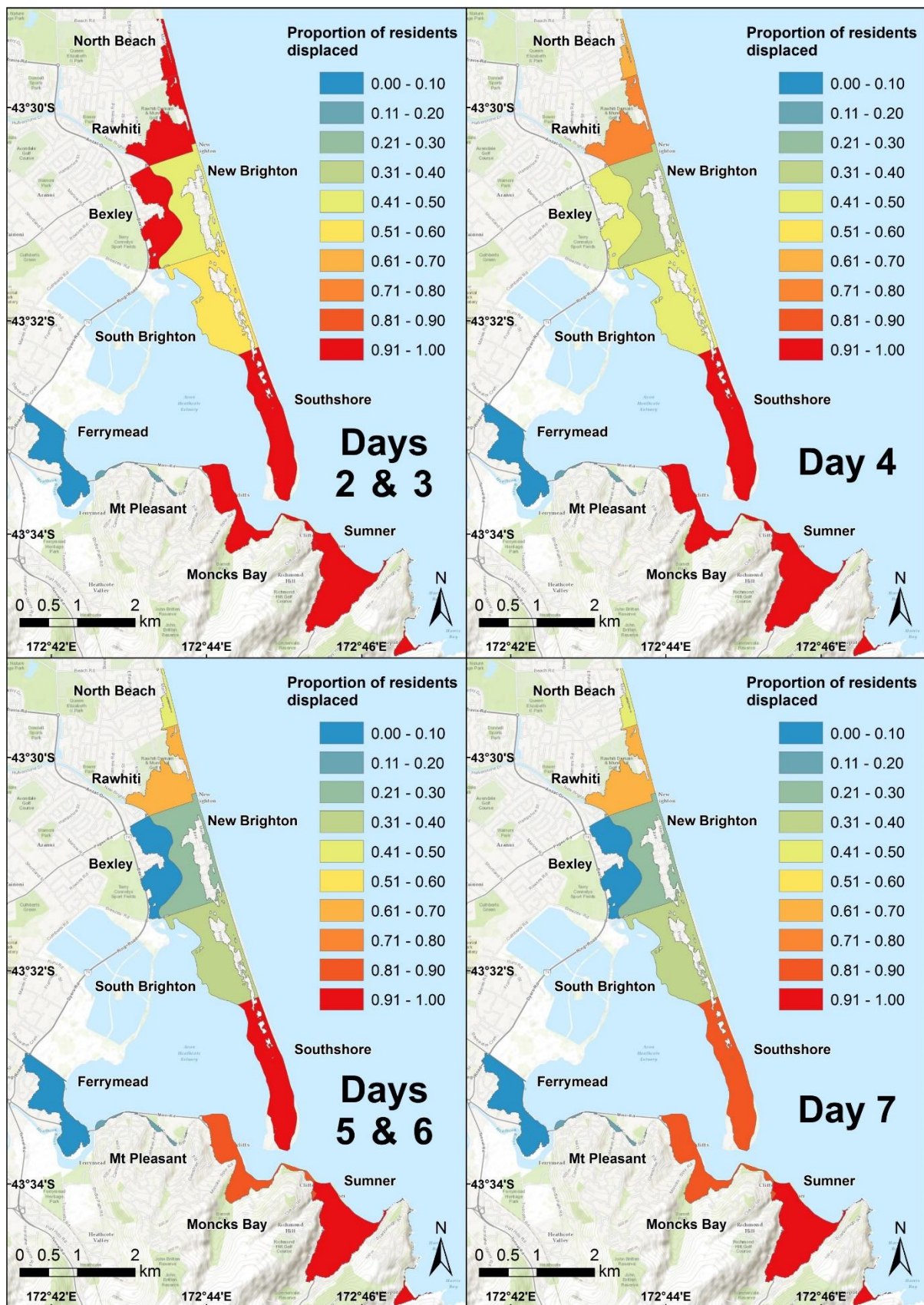


Figure 3.2: Maps showing the proportion of displaced residents per suburb, for different days following the tsunami event (Okada40). The suburbs are clipped to the inundation limit.

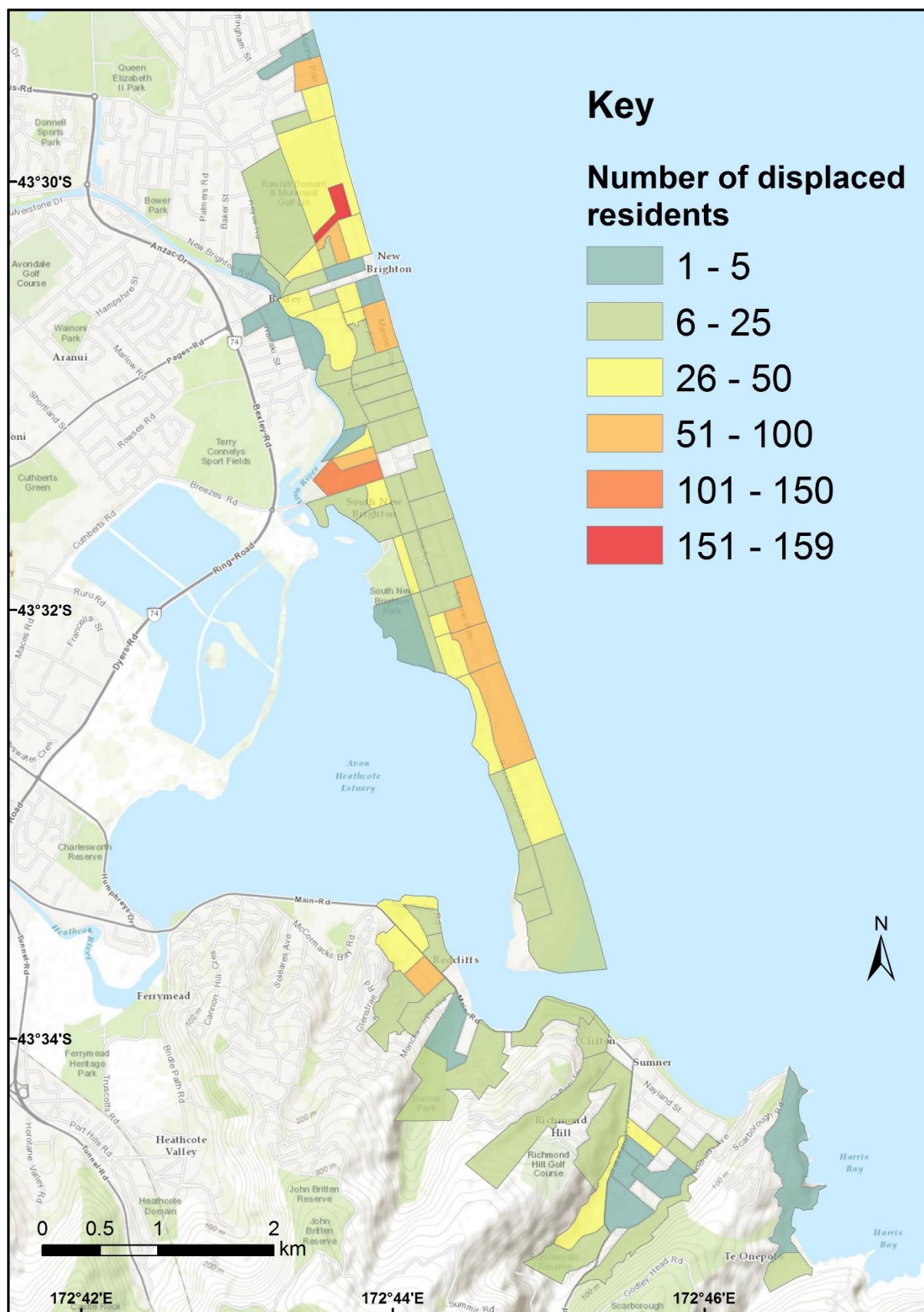


Figure 3.3: Number of residents displaced for between 1 – 7 days per meshblock (excluding those residents displaced for longer), based on the Okada40 scenario.

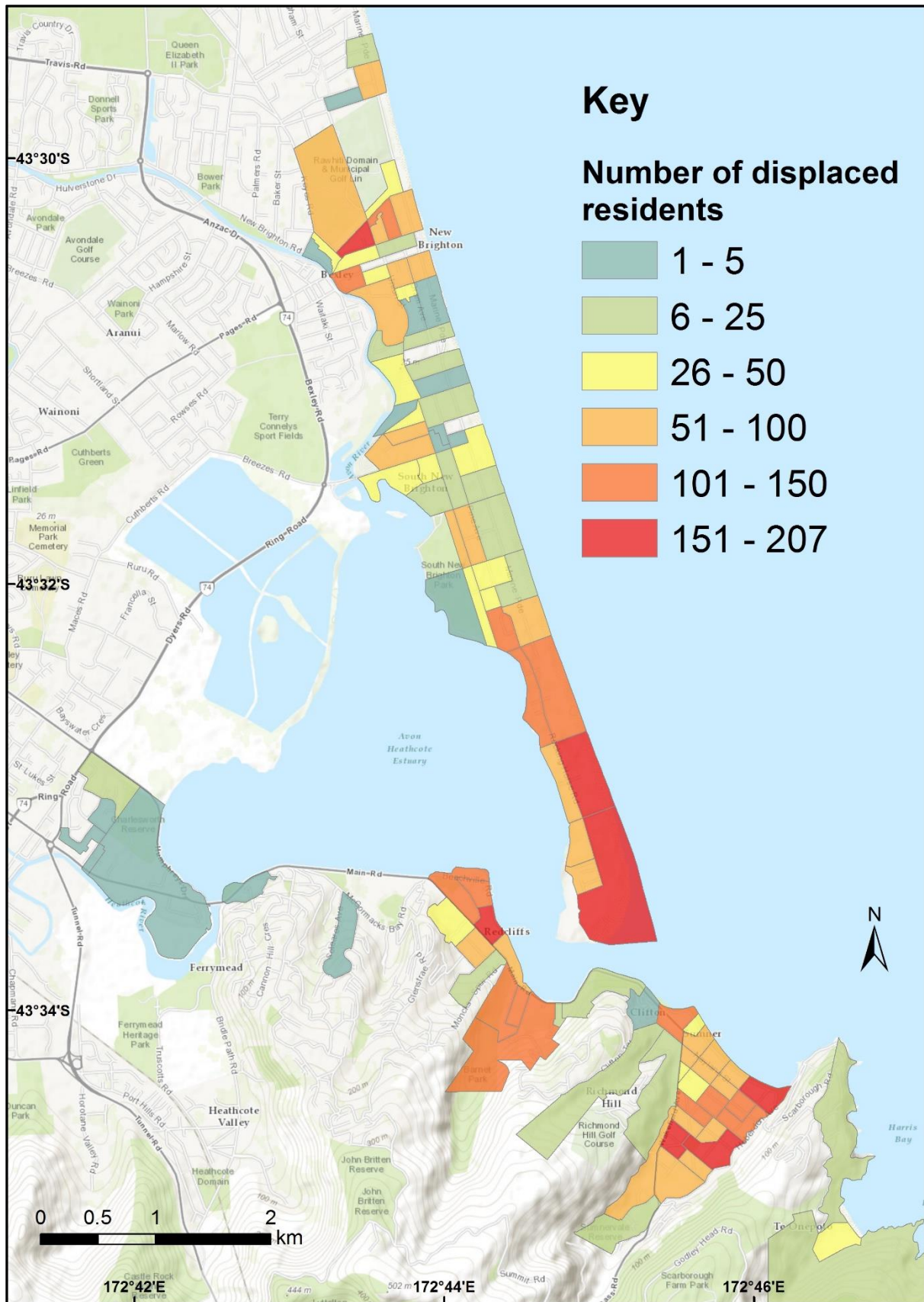


Figure 3.4: Number of residents displaced for at least one week per meshblock, based on the Okada40 scenario.

A sensitivity test was conducted to assess the effect that using different runs of the impact assessment for buildings would have on the habitability results. Table 3.5 shows the total number of uninhabitable residences across different days, for 5 runs of the impact assessment modelling. The variability in results is expected, as each run produces a different distribution of damage states for buildings across the inundation zone (see page 60 & Appendix B). The variation in results is not particularly large, however it does add to the uncertainty within the overall process.

Table 3.5: Sensitivity test of using 5 different runs of the impact assessment model for building damage, as part of the habitability assessment, showing the total number of uninhabitable residences per day.

Number of uninhabitable residences				
Damage State Run	Days 2 & 3	Day 4	Days 5 & 6	Day 7
1	3766	3417	2996	2863
2	3772	3432	3056	2922
3	3771	3400	2979	2852
4	3782	3442	3015	2891
5	3774	3427	3006	2903
Average	3773	3424	3010	2886

3.5 Discussion

Assessing the habitability of residential buildings and displacement of people following a significant natural event such as a tsunami is very important for emergency management planning, particularly to estimate welfare needs and to prioritise areas for response and recovery. The results presented in this chapter may be used as a starting point for assessing habitability and the displacement of residents in Christchurch following a major tsunami

event. The process may also serve as an example or a foundation for continuing research into assessing habitability and displacement using GIS.

3.5.1 Discussion of results

The results are an indication of residential habitability and the number of displaced residents that will require accommodation following the tsunami event. They are most useful for showing the change over a short timeframe, and where the most impacted areas are. The modelling outputs provided may be used as a basis for emergency management exercising and planning, but should not be considered accurate.

The results are an improvement upon only using damage states from building impact assessments, as currently implemented in the RiskScape software, due to the increased information regarding habitability. The factors considered in the modelling are those most easily incorporated into GIS. Additional factors should be considered when reviewing the results, as detailed in section 3.5.3.

Overall, the results reflect the expected outcome from the modelling. The number of habitable residential dwellings and displaced residents is significantly influenced by factors other than building damage alone. This is particularly apparent when reviewing the results from suburbs with a mix of damage states such as New Brighton and Rawhiti. Within these suburbs, there is a significant trend towards more residences being habitable for each day within the first week, and the corresponding reduction in displaced residents. For heavily damaged suburbs such as Moncks Bay and Sumner, where access is also restricted for several days, the habitability of residences is restored more slowly, due to slower recovery of utilities and a greater proportion of buildings with at least moderate damage (requiring significant repair before restoring habitability).

3.5.2 Uncertainty and limitations

There are many sources of uncertainty in the habitability modelling, and these must be taken into account when considering the results. In many cases, it was necessary to make

assumptions based on very limited knowledge, especially in attempting to estimate the outcomes of very complicated situations. The uncertainty and assumptions in each step of the process are noted within the methodology. In general, a lack of previous studies into estimating the potential post-event habitability or displacement of people means there is little to compare the results to. The studies that have been undertaken consider different natural events and contexts, and few are focused on tsunami events. Therefore, there is no way to validate the results of the habitability modelling at this stage. Some of the limitations may be addressed by consulting with experts on each of the contributing factors to habitability or displacement, including those not included in the GIS modelling listed below.

3.5.3 Other factors

There are many other factors that determine post-event habitability and influence residents' decisions whether to return to their homes (Table 3.1). Most of these are indirect or intangible factors that are difficult or impractical to model using GIS. Some of the factors are listed here, and discussed in the context of the tsunami scenario affecting Christchurch. These factors should be considered in combination with the results of the building habitability and human displacement modelling using GIS. For scenario exercising (e.g. by Canterbury CDEM), the factors listed here may be considered via consultation with experts in each topic, and with people knowledgeable regarding the local context, in order to improve the realism of the scenario. Additionally, these factors indicate areas that may be valuable to focus on for future research into habitability and displacement.

- Clean-up time: Buildings with minor damage (DS1) will have experienced tsunami inundation that requires clean-up. In many cases this will delay the reoccupation of a residence. The timeframe for this is very difficult to estimate, as it can vary significantly depending on the specific impacts to a building. Studies into clean-up following flooding events do not provide specific timeframes, and information provided during the interviews was highly variable, reflecting the complexity of the topic. More research into restoration of buildings following tsunami inundation would be valuable.

- Contamination: The damage to the wastewater infrastructure may result in the spilling of sewerage that contaminates the environment, including residential dwellings. This is difficult to model, as the impact to the wastewater system is only able to be broadly considered in terms of functional or non-functional areas based on expert opinion. A complicated analysis of the impact to the wastewater network would be needed to consider this factor using GIS. Ongoing research and lessons from the wastewater impacts of the CES will assist with future assessments of possible tsunami impacts. Within the Okada40 scenario, however, there is no inundation of the Bromley oxidation ponds or wastewater treatment plant, therefore this key facility will not be directly impacted
- Community functionality: This category includes the functioning of local schools, businesses and public services. Even if a residence is considered habitable, the normal occupants may not want to live there due to the impracticality of living within a dysfunctional local community. This may be of most relevance during the short-medium term recovery timeframe, as opposed to the first week when the communities will be focused on responding to the event.
- Intangible factors: These include security, perception of risk and psychosocial factors that may influence residents' decisions to return to their homes. Of particular note are those residents who have lived through the CES, and may have a low tolerance for enduring recovery from another major natural disaster, preferring instead to relocate.
- Demographics: The habitability modelling does not consider the demographics of the population within the affected area. As noted in the literature, some groups of people are more likely to return than others e.g. car owners or those with significant attachment to the local community, such as the elderly (González-Riancho et al., 2013; Levine et al., 2007). These factors were not incorporated into the modelling, despite being able to be addressed using census data, due to the lack of studies considering the specific New Zealand context, which varies significantly from overseas contexts.

- Season: The time of year and weather may have an influence on whether residents choose to return to their homes. For example, in winter the importance of functional heating is much greater than in summer (Wright and Johnston, 2010).

3.5.4 Potential future research

The habitability modelling methodology presented in this chapter is an example of how the process may be employed using GIS. The process highlights the factors leading to building habitability and the decisions of residents to return. There are several avenues of potential future research that may improve the process, both for the specific tsunami scenario affecting Christchurch and also for post-event habitability modelling in general.

- The relative influence of factors leading to habitability could be further investigated. Currently, the literature is generally vague on this topic, with only rough estimates of the importance of each factor (e.g. loss of electricity is more disruptive than loss of water, Seville et al., 2014; Wright and Johnston, 2010). It would be valuable to quantitatively assess the relative influence of each factor, in order to create more realistic weightings for GIS modelling.
- It would be valuable to assess empirically the timeframe of clean-up following flooding events in the New Zealand context. Flooding events are likely to have similar impacts to tsunami inundation, in those cases where structural damage is not significant. An empirically-derived recovery curve, considering the timeframe before reoccupation dependent on inundation depth and construction type, could be developed.
- The functionality of utilities is currently based on rough polygons created following expert consultation. As the impacts of tsunami on infrastructure are better resolved using fragility functions, this part of the process should be improved.
- GIS may be used to assess the wider community functioning following an event (e.g. the functionality of schools, businesses, and services), which could augment the results of habitability assessed for individual residential dwellings. This concept is similar to the “neighbourhood liveability index” proposed by Giovinazzi et al. (2012) for assessing community habitability factors following the CES. The

assessment could be based on building damage modelling for assets other than residential dwellings, combined with factors weighted to their impact (e.g. how water or power functionality affects businesses or schools).

- The habitability assessment method could be incorporated into the RiskScape software, and used for a variety of hazard scenarios. This would require accurate asset databases of both buildings and infrastructure, as well as the appropriate fragility functions to assess the impacts.

3.5.5 Summary

The main objective of the chapter was to estimate the habitability and human displacement within the first week following the beginning of the tsunami event. This was achieved as best as possible given the scarcity of relevant information within the literature, and considering the lack of significantly developed modelling approaches for habitability and displacement, especially for tsunami events. The results are an improvement over considering only building damage state, and may enhance emergency management planning and scenario exercising. The developed methodology and information from the literature review and interviews may be used as a basis for further development into assessments of building habitability and human displacement, using GIS modelling. This may include incorporating additional influential factors other than damage state into the RiskScape software. The methodology may be applied to a variety of natural hazards.

Chapter 4: Conclusions and recommendations

4.1 Conclusions

The purpose of this thesis was to model the impacts of a major far-field tsunami on Christchurch, New Zealand, focusing on the damage to buildings, the habitability of residential dwellings, and displacement of people post-event. Although inundation modelling for a far-field event was available, a detailed assessment of the impacts to communities had not been undertaken previously. This study developed a methodology which provided results to fulfil the thesis objectives, including estimates on the extent and degree of building damage, and estimates on the habitability of residences and human displacement both spatially and temporally for the first week following the tsunami wave arrival. The results provide resources for emergency management planning and scenario exercising, and the findings of this thesis contribute to the RiskScape programme.

4.1.1 Assessment of building damage

The considerable increase in tsunami-related literature following the 2004 IOT was particularly useful for this study, especially the work on fragility functions for estimating the tsunami impacts on buildings. The impact assessment process was used for estimating impacts on buildings, by relating the inundation modelling and exposed building attributes to relevant fragility functions, to produce estimates of damage state. An up-to-date database of building assets within the potential inundation zone of coastal Christchurch was created by field surveying, post-processing of building footprints using GIS, and merging building attribute data obtained from CCC. The post-processing of building footprints was time-consuming, as there were many changes to the building stock within the inundation zone following the CES. However, the field surveying of building attributes was relatively efficient, with more than 1,200 buildings surveyed in approximately 25 hours, with the assistance of one or two other people for about half of that time. The efficiency of surveying demonstrates how building attributes for a study area may be collected quickly,

if only the critical attributes for impact assessments are focused on. In locations that have not suffered extensive changes to the building stock, post-processing of building footprints may not be as time-consuming, and therefore an accurate asset database may be efficiently created. The difference in impact modelling results between the newly created database and the RiskScape database demonstrates the value in examining existing datasets and updating where necessary. The up-to-date database within the inundation zone is a contribution to the larger RiskScape database, and may be used for impact assessments considering different natural hazards.

The results of the impact assessment for building damage indicate the degree and extent of damage is closely tied to the inundation depths from the tsunami inundation modelling, as expected. The suburbs which experience the greatest inundation depths are extensively damaged, especially the low-lying areas of Sumner and Moncks Bay/Redcliffs. Within the overall Okada40 scenario inundation zone, approximately 950 buildings are estimated as collapsed or washed away, 2,150 suffer moderate to complete damage, and 1,600 experience minor or no damage.

4.1.2 Assessment of building habitability and human displacement

A literature review was conducted to examine studies that consider human displacement or building habitability following a major disaster. Studies on building habitability and human displacement following tsunami are very sparse, and therefore information from other natural hazard disasters was used to inform the assessments. To provide more information, particularly for the Christchurch context, interviews were conducted with first-responders to international tsunami events and those with recent experience of flooding and earthquakes in Christchurch. The main findings of the literature review and interviews were that building damage, access and provision of power, water and wastewater are all important factors leading to habitability, and some attempts have been made in other studies to model habitability and displacement considering these factors. There are many other contributing factors that are important, such as security and psychosocial factors, however these are difficult to incorporate into modelling.

A methodology was developed for estimating the habitability of residences and displacement of people using GIS modelling, and considered the factors of building damage, access, and functioning of utilities (power, water, and wastewater). The relative influence of the factors was weighted based on the information from the literature review and interviews. The building damage data used were outputs from the impact modelling to buildings. Spatial and temporal data for access and functioning of utilities were created based upon expert consultation, and consideration of the literature and local context. Overall, the lack of specific information regarding habitability and displacement following tsunami events, and the difficulty of applying available literature to the local context, created challenges for the assessment. However, although many assumptions were necessarily made during the process, the methodology demonstrates how habitability and displacement may be modelled using GIS, and highlights areas of potential future research. The results of the habitability and displacement modelling show the number of uninhabitable residences and number of people displaced for each day following the tsunami arrival, and are displayed in various forms, including by census meshblock and suburb. The results reflect the expected outcome, which is that habitability and displacement are influenced by more than building damage state alone. The heavily damaged suburbs of Sumner and Moncks Bay show only slight reduction in the number of uninhabitable buildings across the first week. New Brighton and Rawhiti, which experienced a greater mix of damage states, showed significant reduction in the number of uninhabitable buildings per day, reflecting the influence of factors other than damage state, as access routes and utilities are progressively restored.

4.1.3 Summary

The results of this thesis are directly applicable to emergency management planning and scenario exercising, which is an objective of the research. The spatial extent and degree of building damage is a direct impact of tsunami inundation, and is one of the key considerations for emergency management. This is because building damage has a profound influence on the functioning of communities post-event, as well as the response and recovery requirements. The assessment of residential habitability and displacement of

people is important for emergency management planning of welfare needs following a major tsunami event. Spatial and temporal modelling for the first week following tsunami arrival shows the areas of greatest welfare need, and how quickly they may recover. There are also several lessons that emerge from this research, which inform the recommendations and research directions as follows.

4.2 Recommendations and research directions

This section details the recommendations and potential future research directions for tsunami impact and habitability assessments. A greater level of detail is provided in the “Discussion” sections of Chapters 2 and 3.

4.2.1 Recommendations

- The most relevant fragility functions for assessing tsunami impacts to buildings in New Zealand are those developed by Suppasri et al. (2013).
- Field surveying of building attributes has been demonstrated to be efficient, provided a suitable plan of areas or transects are produced. It is recommended that only the critical attributes applicable for impact assessments are collected, despite the possibility of surveying many attributes of buildings. These include the building purpose, construction type, number of storeys and ground floor height. There is little purpose in collecting attributes that are not directly usable for a project, and it is preferable to instead spend time surveying a greater sample size.
- The RiACT application could be refined for the option of rapid collection of a small number of attributes, as opposed to defaulting to a format designed for surveying buildings in detail.
- It would be valuable to be able to export the disaggregated outputs of the RiskScape software into a third party GIS (e.g. ArcMap). This would allow more detailed processing to occur, and aggregation into units other than those within RiskScape.

- Adding an option within the RiskScape software to perform multiple runs of the modelling at once would refine results. Other than the lack of the most relevant in-built fragility functions for tsunami, the requirement to model a single run at a time was a significant drawback.
- Factors influencing building habitability and human displacement other than building damage state could be incorporated into the RiskScape software.

4.2.2 Research directions

- A study into the specific differences between the building stock in Japan and New Zealand and how they may influence structural vulnerability to tsunami effects would be valuable, in order to further determine the applicability of fragility functions developed using data from the 2011 GEJT.
- The relative influence of factors contributing to post-event building habitability could be further investigated. This may involve detailed surveying of buildings, infrastructure and populations following an event. This could be undertaken for tsunami events or any natural hazard-induced disaster, as the literature is generally sparse on this topic. The research could ultimately be used to produce weightings of factors that are based on statistics, instead of approximations of relative influence.
- An empirically derived recovery curve for time before re-occupation of buildings, based on surveying following flooding or tsunami inundation, would be valuable for estimating clean-up times following these events. Clean-up time is a contributing factor to building habitability.
- A GIS modelling methodology considering the wider functioning of communities could be developed, incorporating such factors as the functionality of schools, business and infrastructure. This would enhance impact assessments for communities, and enable better emergency management planning and scenario exercising to take place.

- The building damage, residential habitability and human displacement modelling undertaken within this thesis can be used as a guide for assessments considering other scenarios, locations, and different natural hazards.

References

- Abramson, D., Van Alst, D., Merdjanoff, A., Piltch-Loeb, R., Beedasy, J., Findley, P., Peek, L., Mordy, M., Moroso, S., Ocasio, K., Soo Park, Y., Sury, J., Tobin-Gurley, J., 2015. The Hurricane Sandy Place Report: Evacuation Decisions, Housing Issues and Sense of Community. Rutgers University School of Social Work, New York University College.
- Beban, J.G., Cousins, W.J., Doody, B.J., Becker, J.S., Wright, K.C., 2013. Water needs and the availability of water in post- earthquake Wellington City, and the significance of social factors in determining community resilience. GNS Science Consultancy Report 2013/15, 54p.
- Bell, R., Holden, C., Power, W., Wang, X., Downes, G., 2014. Hikurangi margin tsunami earthquake generated by slow seismic rupture over a subducted seamount. *Earth Planet. Sci. Lett.* 397, 1–9.
- BRANZ, 2004. Restoring a house after flood damage. 12p.
- Bryant, E., 2008. Tsunami: the underrated hazard. Springer, Dordrecht.
- Buxton, R., Wright, K.C., Daly, M.C., Timar, L., Mieler, D., 2014. Single Infrastructure Failures: Capturing outage information for MERIT Modelling the Economics of Resilient Infrastructure Tool. ERI Research Report 2014/01, 56p.
- Canterbury Earthquake Recovery Authority, 2014. Canterbury Wellbeing Index: Population. 13p.
- Chang, S.E., Eguchi, R.T., Seligson, H.A., 1996. Estimation of the economic impact of multiple lifeline disruption: Memphis light, gas and water division case study.
- Chang, S.E., McDaniels, T.L., Mikawoz, J., Peterson, K., 2007. Infrastructure failure interdependencies in extreme events: Power outage consequences in the 1998 Ice Storm. *Nat. Hazards* 41, 337–358.
- Charvet, I., Ioannou, I., Rossetto, T., Suppasri, A., Imamura, F., 2014a. Empirical fragility assessment of buildings affected by the 2011 Great East Japan tsunami using improved statistical models. *Nat. Hazards* 73, 951–973.
- Charvet, I., Suppasri, A., Imamura, F., 2014b. Empirical fragility analysis of building damage caused by the 2011 Great East Japan tsunami in Ishinomaki city using ordinal regression, and influence of key geographical features. *Stoch. Environ. Res. Risk Assess.* 28, 1853–1867.
- Christchurch Engineering Lifelines Group, 1997. Risks & Realities: A Multi-disciplinary Approach to the Vulnerability of Lifelines to Natural Hazards. Centre for Advanced Engineering, University of Caterbury.

- Comerio, M.C., 1997. Housing issues after disasters. *J. Contingencies Cris. Manag.* 5, 166–178.
- Cousins, W.J., Power, W.L., Palmer, N.G., Reese, S., Tejakusuma, I.G., Nugrahadhi, S., 2007. Damage and Casualties in the South Java Tsunami of 17th July 2006. 2007 New Zeal. Soc. Earthq. Eng. Conf. 1–8.
- Dall’Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., Dominey-Howes, D., 2009. A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage. *Nat. Hazards Earth Syst. Sci.* 9, 1557–1565.
- Dall’Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., Dominey-Howes, D., 2009. Assessing the vulnerability of buildings to tsunami in Sydney. *Nat. Hazards Earth Syst. Sci.* 9, 2015–2026.
- Dall’Osso, F., Maramai, A., Graziani, L., Brizuela, B., Cavalletti, A., Gonella, M., Tinti, S., 2010. Applying and validating the PTVA-3 Model at the Aeolian Islands, Italy: assessment of the vulnerability of buildings to tsunamis. *Nat. Hazards Earth Syst. Sci.* 10, 1547–1562.
- De Lange, W.P., Healy, T.R., 1986. New Zealand tsunamis 1840–1982. *New Zeal. J. Geol. Geophys.* 29, 115–134.
- Devane, M.L., Moriarty, E.M., Wood, D., Webster-Brown, J., Gilpin, B.J., 2014. The impact of major earthquakes and subsequent sewage discharges on the microbial quality of water and sediments in an urban river. *Sci. Total Environ.* 485–486, 666–680.
- Dias, W.P.S., Yapa, H.D., Peiris, L.M.N., 2009. Tsunami vulnerability functions from field surveys and Monte Carlo simulation. *Civ. Eng. Environ. Syst.* 26, 181–194.
- Dominey-Howes, D., Goff, J., 2013. Tsunami Risk Management in Pacific Island Countries and Territories (PICTs): Some Issues, Challenges and Ways Forward. *Pure Appl. Geophys.* 170, 1397–1413.
- Francis, M.J., Yeh, H., 2006. Tsunami Inundation Scour of Roadways, Bridges and Foundations: Observations and Technical Guidance from the Great Sumatra Andaman Tsunami. EERI/FEMA NEHRP 2006 Professional Fellowship Report.
- Fraser, S., Matsuo, I., Leonard, G.S., Murakami, H., 2012. Tsunami evacuation: Lessons from the Great East Japan earthquake and tsunami of March 11th 2011. GNS Science Report 2012/17, 89p.
- Fraser, S., Power, W., Wang, X., Wallace, L., Mueller, C., Johnston, D., 2014. Tsunami inundation in Napier, New Zealand, due to local earthquake sources. *Nat. Hazards* 70, 415–445.
- Fraser, S., Raby, A., Pomonis, A., Goda, K., Chian, S., Macabuag, J., Offord, M., Saito, K., Sammonds, P., 2013. Tsunami damage to coastal defences and buildings in the March

- 11th 2011 M w 9.0 Great East Japan earthquake and tsunami. *Bull. Earthq. Eng.* 11, 205–239.
- Fraser, S.A., Power, W.L., Wang, X., Wallace, L.M., Mueller, C., Johnston, D.M., 2014. Tsunami inundation in Napier, New Zealand, due to local earthquake sources. *Nat. Hazards* 70, 415–445.
- Fujimi, T., Tatano, H., 2012. Estimation of indirect economic loss caused by house destruction in a natural disaster. *Nat. Hazards* 61, 1367–1388.
- Fussell, E., Sastry, N., Vanlandingham, M., 2010. Race, socioeconomic status, and return migration to New Orleans after Hurricane Katrina. *Popul. Environ.* 31, 20–42.
- Ghobarah, A., Saatcioglu, M., Nistor, I., 2006. The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure. *Eng. Struct.* 28, 312–326.
- Gillibrand, P., Arnold, J., Lane, E., Roulston, H., Enright, M., 2011. Modelling Coastal Inundation in Canterbury from a South American Tsunami. Environment Canterbury report number R11/08.
- Giovinazzi, S., Stevenson, J.R., Mitchell, J., Mason, A., 2012. Temporary housing issues following the 22nd Christchurch Earthquake, NZ. In: Unpublished Paper Presented at the 2012 NZSEE Conference.
- GNS Science, 2014. New Zealand Tsunami Database. Unpublished data.
- GNS Science/NIWA, 2014. The RiskScape Process [WWW Document]. URL https://wiki-riskscape.niwa.co.nz/index.php/The_RiskScape_Process
- Goff, J., Nichol, S., Kennedy, D., 2010. Development of a palaeotsunami database for New Zealand. *Nat. Hazards* 54, 193–208.
- Gokon, H., Koshimura, S., Imai, K., Matsuoka, M., Namegaya, Y., Nishimura, Y., 2014. Developing fragility functions for the areas affected by the 2009 Samoa earthquake and tsunami. *Nat. Hazards Earth Syst. Sci.* 14, 3231–3241.
- González-Riancho, P., Aguirre-Ayerbe, I., García-Aguilar, O., Medina, R., González, M., Aniel-Quiroga, I., Gutiérrez, O.Q., Álvarez-Gómez, J. a., Larreynaga, J., Gavidia, F., 2013. Integrated tsunami vulnerability and risk assessment: application to the coastal area of El Salvador. *Nat. Hazards Earth Syst. Sci. Discuss.* 1, 2883–2943.
- Gopinath, G., Løvholt, F., Kaiser, G., Harbitz, C.B., Srinivasa Raju, K., Ramalingam, M., Singh, B., 2014. Impact of the 2004 Indian Ocean tsunami along the Tamil Nadu coastline: field survey review and numerical simulations. *Nat. Hazards* 72, 743–769.
- Grilli, S., O'Reilly, C., Harris, J., Bakhsh, T., Tehranirad, B., Banihashemi, S., Kirby, J., Baxter, C.P., Eggeling, T., Ma, G., Shi, F., 2015. Modeling of SMF tsunami hazard along the upper US East Coast: detailed impact around Ocean City, MD. *Nat. Hazards* 76, 705–746.

- Heidarzadeh, M., Murotani, S., Satake, K., Ishibe, T., Gusman, A.R., 2015. Source model of the 16 September 2015 Illapel, Chile Mw 8.4 earthquake based on teleseismic and tsunami data. *Geophys. Res. Lett.* 2015GL067297.
- Hori, M., Schafer, M.J., 2010. Social costs of displacement in Louisiana after Hurricanes Katrina and Rita. *Popul. Environ.* 31, 64–86.
- Horspool, N., Cousins, W.J., Power, W.L., 2015. Review of Tsunami Risk facing New Zealand: A 2015 update. GNS Science Consultancy Report 2015/38, 44p.
- Horwich, G., 2000. Economic Lessons of the Kobe Earthquake. *Econ. Dev. Cult. Change* 48, 521–542.
- Jelínek, R., Krausmann, E., González, M., Álvarez-Gómez, J.A., Birkmann, J., Welle, T., 2012. Approaches for tsunami risk assessment and application to the city of Cádiz, Spain. *Nat. Hazards* 60, 273–293.
- Jha, A.K., Dwyne, J.E., 2010. Safer homes, stronger communities: a handbook for reconstructing after natural disasters. World Bank Publications.
- King, A., Bell, R., 2009. RiskScape Project: 2004 - 2008. GNS Science Consultancy Report 2009/247, 162p.
- King, D.N., 2015. Tsunami hazard, assessment and risk in Aotearoa–New Zealand: A systematic review AD 1868–2012. *Earth-Science Rev.* 145, 25–42.
- Koshimura, S., Kayaba, S., Matsuoka, M., 2010. Integrated approach to assess the impact of tsunami disaster. *Safety, Reliab. Risk Struct. Infrastructures Eng. Syst.* 2302–2307.
- Koshimura, S., Namegaya, Y., Yanagisawa, H., 2009. Tsunami fragility: A new measure to identify tsunami damage. *J. Disaster Res.* 4, 479–488.
- Koshimura, S., Oie, T., Yanagisawa, H., Imamura, F., 2009. Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia. *Coast. Eng. J.* 51, 243–273.
- Lane, E., Arnold, J., Sykes, J., Roulston, H., 2012. Modelling coastal inundation in Christchurch and Kaiapoi from a South American tsunami using topography from after the 2011 February earthquake. Environment Canterbury report number R12/38.
- Lane, E., Kohout, A., Chiaverini, A., Arnold, J., 2014. Updated inundation modelling in Canterbury from a South American tsunami. NIWA Client Report, CHC2014-100 and Environment Canterbury Report No. R14/78: 54.
- Lane, E.M., Gillibrand, P.A., Arnold, J.R., Walters, R.A., 2011. Tsunami inundation modelling using RiCOM. *Aust. J. Civ. Eng.* 9, 83–98.
- Leelawat, N., Suppasri, A., Charvet, I., Imamura, F., 2014. Building damage from the 2011 Great East Japan tsunami: quantitative assessment of influential factors. *Nat. Hazards* 73, 449–471.

- Leelawat, N., Suppasri, A., Charvet, I., Kimura, T., Sugawara, D., Imamura, F., 2015. A Study on Influential Factors on Building Damage in Kesennuma, Japan from the 2011 Great East Japan Tsunami. *Eng. J.* 19, 105–116.
- Leone, F., Lavigne, F., Paris, R., Denain, J.-C., Vinet, F., 2011. A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability. *Appl. Geogr.* 31, 363–375.
- Levine, J.N., Esnard, a.-M., Sapat, a., 2007. Population Displacement and Housing Dilemmas Due to Catastrophic Disasters. *J. Plan. Lit.* 22, 3–15.
- Lin, S.-L., King, A., Wright, K., Matcham, I., 2014. RiACT User Manual. GNS Science.
- Love, T., 2011. Population movement after natural disasters: a literature review and assessment of Christchurch data, Sapere Research Group. 21p.
- Macabuag, J., Rossetto, T., 2014. Towards the Development of a Method for Generating Analytical Tsunami Fragility Functions. In: 2nd European Conference on Earthquake Engineering and Seismology.
- Marchand, M., Buurman, J., Pribadi, A., Kurniawan, A., 2009. Damage and casualties modelling as part of a vulnerability assessment for tsunami hazards: a case study from Aceh, Indonesia. *J. Flood Risk Manag.* 2, 120–131.
- Mas, E., Koshimura, S., Suppasri, A., Matsuoka, M., Matsuyama, M., Yoshii, T., Jimenez, C., Yamazaki, F., Imamura, F., 2012. Developing Tsunami fragility curves using remote sensing and survey data of the 2010 Chilean Tsunami in Dichato. *Nat. Hazards Earth Syst. Sci.* 12, 2689–2697.
- McDaniels, T., Chang, S., Peterson, K., Mikawoz, J., Reed, D., 2007. Empirical Framework for Characterizing Infrastructure Failure Interdependencies. *J. Infrastruct. Syst.* 13, 175–184.
- Miles, S.B., Chang, S.E., 2006. Modeling community recovery from earthquakes. *Earthq. Spectra* 22, 439–458.
- Murao, O., Nakazato, H., 2010. Vulnerability functions for buildings based on damage survey data in Sri Lanka after the 2004 Indian Ocean tsunami. In: International Conference on Sustainable Built Environment (ICSBE-2010).
- Najihah, R., Effendi, D.M., Hairunnisa, M.A., Masiri, K., 2014. Tsunami vulnerability assessment mapping for the west coast of Peninsular Malaysia using a geographical information system (GIS). *IOP Conf. Ser. Earth Environ. Sci.* 18, 12047.
- Nakanishi, H., Black, J., Matsuo, K., 2014. Disaster resilience in transportation: Japan earthquake and tsunami 2011. *Int. J. Disaster Resil. Built Environ.* 5, 341–361.
- Norio, O., Ye, T., Kajitani, Y., Shi, P., Tatano, H., 2011. The 2011 eastern Japan great earthquake disaster: Overview and comments. *Int. J. Disaster Risk Sci.* 2, 34–42.

- NZIER, 2015. Tsunami risk facing New Zealand. New Zealand Institute of Economic Research.
- Omira, R., Baptista, M.A., Miranda, J.M., Toto, E., Catita, C., Catalão, J., 2010. Tsunami vulnerability assessment of Casablanca-Morocco using numerical modelling and GIS tools. *Nat. Hazards* 54, 75–95.
- Papadopoulos, G.A., Dermentzopoulos, T., 1998. A Tsunami Risk Management Pilot Study in Heraklion, Crete. *Nat. Hazards* 18, 91–118.
- Papathoma, M., Dominey-Howes, D., 2003. Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece. *Nat. Hazards Earth Syst. Sci.* 3, 733–747.
- Papathoma, M., Dominey-Howes, D., Zong, Y., Smith, D., 2003. Assessing tsunami vulnerability, an example from Herakleio, Crete. *Nat. Hazards Earth Syst. Sci.* 3, 377–389.
- Paulik, R., 2015. RiskScape Wiki: New Zealand Building Inventory [WWW Document]. URL https://wiki-riskscape.niwa.co.nz/index.php/File:New_Zealand_Building_Inventory.pdf (accessed 1.17.15).
- Peacock, W.G., Dash, N., Zhang, Y., 2007. Sheltering and Housing Recovery Following Disaster. In: *Handbook of Disaster Research*. Springer, pp. 258–274.
- Peiris, N., 2006. Vulnerability functions for tsunami loss estimation. In: *First European Conference on Earthquake Engineering and Seismology, a Joint Event of the 13th ECEE & 30th General Assembly of the ESC*, Geneva, Switzerland, Paper.
- Power, W., Downes, G., Stirling, M., 2007. Estimation of Tsunami Hazard in New Zealand due to South American Earthquakes. *Pure Appl. Geophys.* 164, 547–564.
- Power, W., Wallace, L., Reyners, M., 2008. Tsunami hazard posed by earthquakes on the Hikurangi subduction zone interface. *GNS Science Consultancy Report* 2008/40.
- Power, W.L., 2013a. Review of Tsunami Hazard in New Zealand (2013 Update). *GNS Science Consultancy Report* 2013/131. 222p.
- Power, W.L., 2013b. Tsunami hazard curves and deaggregation plots for 20km coastal sections, derived from the 2013 National Tsunami Hazard Model. *GNS Science Report* 2013/59. 547p.
- Reese, S., Bradley, B.A., Bind, J., Smart, G., Power, W., Sturman, J., 2011. Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. *Earth-Science Rev.* 107, 156–173.
- Reese, S., Cousins, W.J., Power, W.L., Palmer, N.G., Tejakusuma, I.G., Nugrahadi, S., 2007. Tsunami vulnerability of buildings and people in South Java - field observations

- after the July 2006 Java tsunami. *Nat. Hazards Earth Syst. Sci.* 7, 573–589.
- Rodriguez, H., Wachtendorf, T., Kendra, J., Trainor, J., 2006. A snapshot of the 2004 Indian Ocean tsunami: societal impacts and consequences. *Disaster Prev. Manag.* 15, 163–177.
- Ruangrassamee, A., Yanagisawa, H., Foytong, P., Lukkunaprasit, P., Koshimura, S., Imamura, F., 2006. Investigation of tsunami-induced damage and fragility of buildings in Thailand after the December 2004 Indian Ocean tsunami. *Earthq. Spectra* 22, 377–401.
- Sastry, N., 2008. Tracing the Effects of Hurricane Katrina on the Population of New Orleans: The Displaced New Orleans Residents Pilot Study, Population Studies Center Research Report 08-637.
- Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C., Lawrence, M., 2006. HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment. *Nat. Hazards Rev.* 7, 72–81.
- Schmidt, J., Matcham, I., Reese, S., King, A., Bell, R., Henderson, R., Smart, G., Cousins, J., Smith, W., Heron, D., 2011. Quantitative multi-risk analysis for natural hazards: a framework for multi-risk modelling. *Nat. Hazards* 58, 1169–1192.
- Schmidt, J., Turek, G., Matcham, I., Reese, S., Bell, R., King, A., 2007. RiskScape - an innovative tool for multi-hazard risk modelling. *Geophys. Res. Abstr.* 9.
- Schultz, M.T., Gouldby, B.P., Simm, J.D., Wibowo, J.L., 2010. Beyond the factor of safety: Developing fragility curves to characterize system reliability. DTIC Document.
- Seville, E., Stevenson, J., Vargo, J., Brown, C., Giovinazzi, S., 2014. Disruption and Resilience: How Organisations coped with the Canterbury Earthquakes. ERI Research Report 2014/002.
- Seville, E., Stevenson, J., Vargo, J., Brown, C., Giovinazzi, S., 2015. Resilience and Recovery: Business Behaviour following the Canterbury Earthquakes. In: NIST Workshop on the Economics of the Community Disaster Resilience. pp. 1–7.
- Shuto, N., 1993. Tsunami Intensity and Disasters. In: Tinti, S. (Ed.), *Tsunamis in the World SE - 15, Advances in Natural and Technological Hazards Research*. Springer Netherlands, pp. 197–216.
- Sinaga, T.T., Nugroho, A., Lee, Y.-W., Suh, Y., 2011. GIS mapping of tsunami vulnerability: Case study of the Jembrana regency in Bali, Indonesia. *KSCE J. Civ. Eng.* 15, 537–543.
- Smith, K., 2013. *Environmental hazards: assessing risk and reducing disaster*. Taylor & Francis, Hoboken.
- Spence, R., So, E., Jenny, S., Castella, H., Ewald, M., Booth, E., 2008. *The Global*

- Earthquake Vulnerability Estimation System (GEVES): an approach for earthquake risk assessment for insurance applications. *Bull. Earthq. Eng.* 6, 463–483.
- Standards New Zealand, 2009. Risk management - Principles and guidelines (AS/NZS ISO 31000:2009).
- Statistics New Zealand, 2012. Using cellphone data to measure population movements. Wellington.
- Statistics New Zealand, 2014. 2013 Census QuickStats about families and households [WWW Document]. URL <http://www.stats.govt.nz/Census/2013-census/profile-and-summary-reports/qstats-families-households/households.aspx> (accessed 1.23.16).
- Statistics New Zealand, 2016. Meshblock description [WWW Document]. URL <http://datainfolplus.stats.govt.nz/Item/nz.govt.stats/011d668f-1fe2-4820-8957-837aae2bf575>
- Suppasri, A., Koshimura, S., Imamura, F., 2011. Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand. *Nat. Hazards Earth Syst. Sci.* 11, 173–189.
- Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y., Imamura, F., 2013a. Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. *Nat. Hazards* 66, 319–341.
- Suppasri, A., Shuto, N., Imamura, F., Koshimura, S., Mas, E., Yalciner, A., 2013b. Lessons Learned from the 2011 Great East Japan Tsunami: Performance of Tsunami Countermeasures, Coastal Buildings, and Tsunami Evacuation in Japan. *Pure Appl. Geophys.* 170, 993–1018.
- Synolakis, C.E., Bernard, E.N., 2006. Tsunami science before and beyond Boxing Day 2004. *Philos. Trans. A. Math. Phys. Eng. Sci.* 364, 2231–2265.
- Tarbotton, C., Dall’Osso, F., Dominey-Howes, D., Goff, J., 2015. The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: Comparative review and summary of best practice. *Earth-Science Rev.* 142, 120–134.
- Tarbotton, C., Dominey-Howes, D., Goff, J.R., Papathoma-Kohle, M., Dall’Osso, F., Turner, I.L., 2012. GIS-based techniques for assessing the vulnerability of buildings to tsunami: current approaches and future steps. *Geol. Soc. London, Spec. Publ.* 361, 115–125.
- Thusyanthan, N.I., Madabhushi, S.P.G., 2008. Tsunami wave loading on coastal houses: a model approach. *Proc. ICE - Civ. Eng.* 161, 77–86.
- UNISDR, 2009. UNISDR Terminology on Disaster Risk Reduction.
- Unjoh, S., 2012. Tsunami damage to bridge structures in Rikuzen-Takada City and the

- emergency road network recovery actions. In: Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake. pp. 1429–1438.
- Usha, T., Murthy, M.V.R., Reddy, N.T., Mishra, P., 2012. Tsunami vulnerability assessment in urban areas using numerical model and GIS. *Nat. Hazards* 60, 135–147.
- Valencia, N., Gardi, A., Gauraz, A., Leone, F., Guillande, R., 2011. New tsunami damage functions developed in the framework of SCHEMA project: application to European-Mediterranean coasts. *Nat. Hazards Earth Syst. Sci.* 11, 2835–2846.
- Whittle, R., Medd, W., Deeming, H., Kashefi, E., Mort, M., Twigger Ross, C., Walker, G., Watson, N., 2010. After the Rain – learning the lessons from flood recovery in Hull. 176p.
- Wiebe, D.M., Cox, D.T., 2014. Application of fragility curves to estimate building damage and economic loss at a community scale: a case study of Seaside, Oregon. *Nat. Hazards* 71, 2043–2061.
- Wood, N., 2009. Tsunami exposure estimation with land-cover data: Oregon and the Cascadia subduction zone. *Appl. Geogr.* 29, 158–170.
- Wright, K.C., Cousins, W.J., 2014. Evacuation Numbers and Current Evacuation Planning in Wellington Region for a Tsunami Generated by a Large Hikurangi Subduction Zone Earthquake. GNS Science Report 2014/44. 45p.
- Wright, K.C., Johnston, D.M., 2010. Post-earthquake sheltering needs; how loss of structures and services affects decision making for evacuation; Paper Number 31. In: NZSEE Conference.
- Wright, K.C., Johnston, D.M., Cousins, W.J., McBride, S.K., 2012. Estimating post-earthquake welfare and sheltering needs following a Wellington earthquake. In: New Zealand Society for Earthquake Engineering Technical Conference, Christchurch, New Zealand, 13-15 April, 2012. p. 9.

Appendix A: Inundation modelling scenario maps

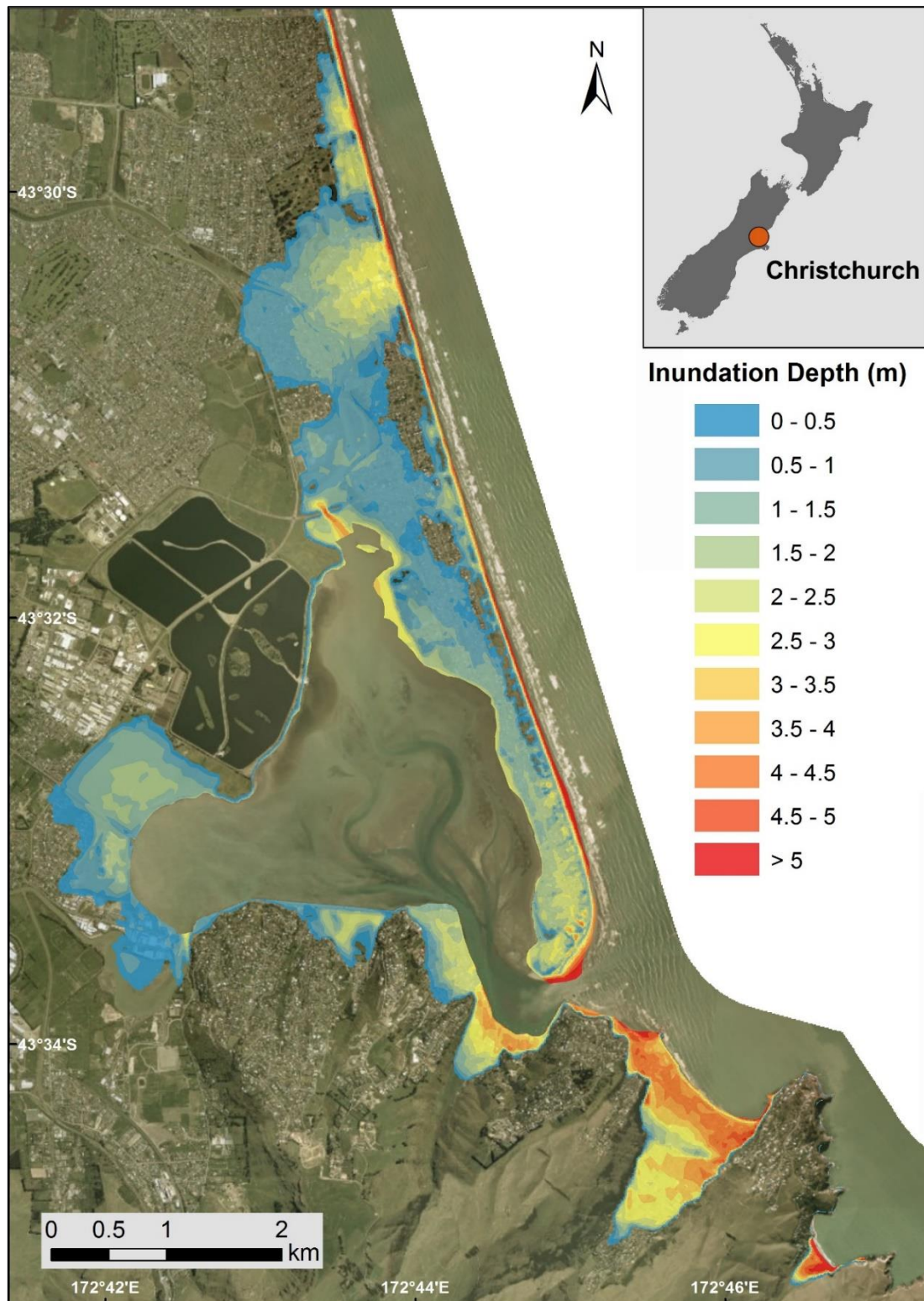


Figure A.1: Inundation modelling of the Okada25A scenario for Christchurch, showing the inundation depths.

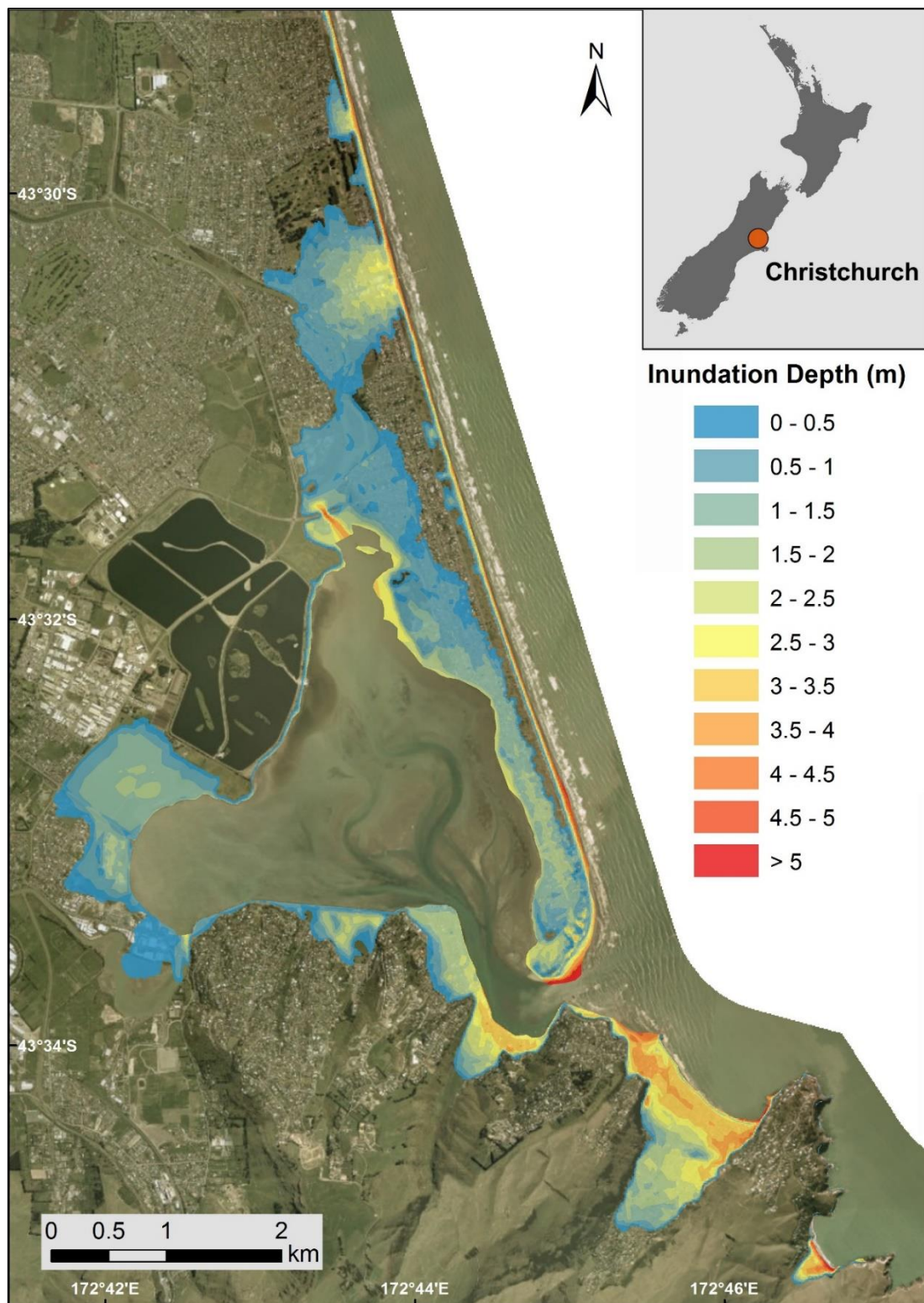


Figure A.2: Inundation modelling of the Okada25B scenario for Christchurch, showing the inundation depths.

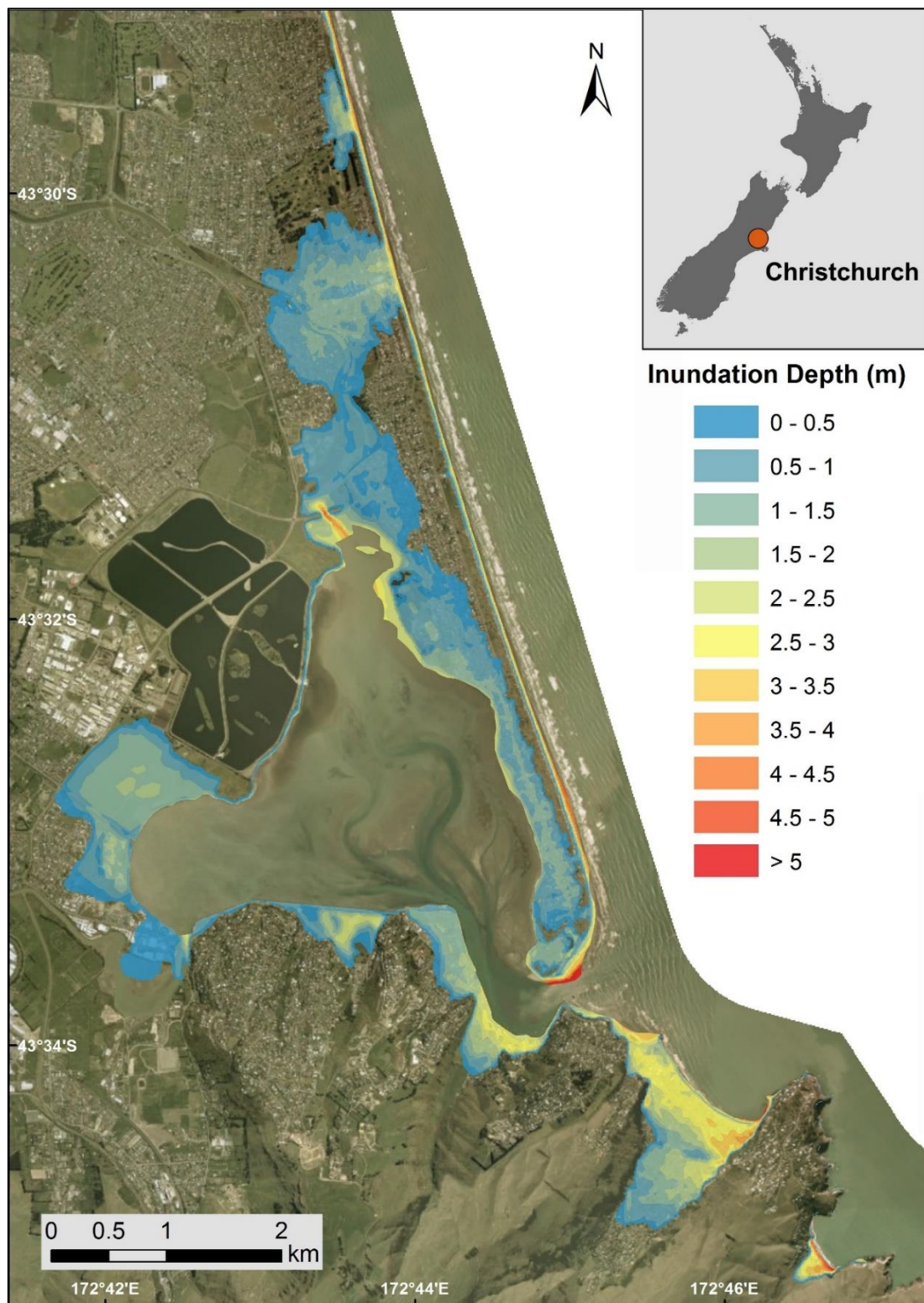


Figure A.3: Inundation modelling of the Okada30 scenario for Christchurch, showing the inundation depths.

Appendix B: Distribution of building damage states in Redcliffs



Figure B.1: Example map of Redcliffs showing the damage state distribution of a single run (#2) of the impact assessment modelling for the Okada40 scenario.

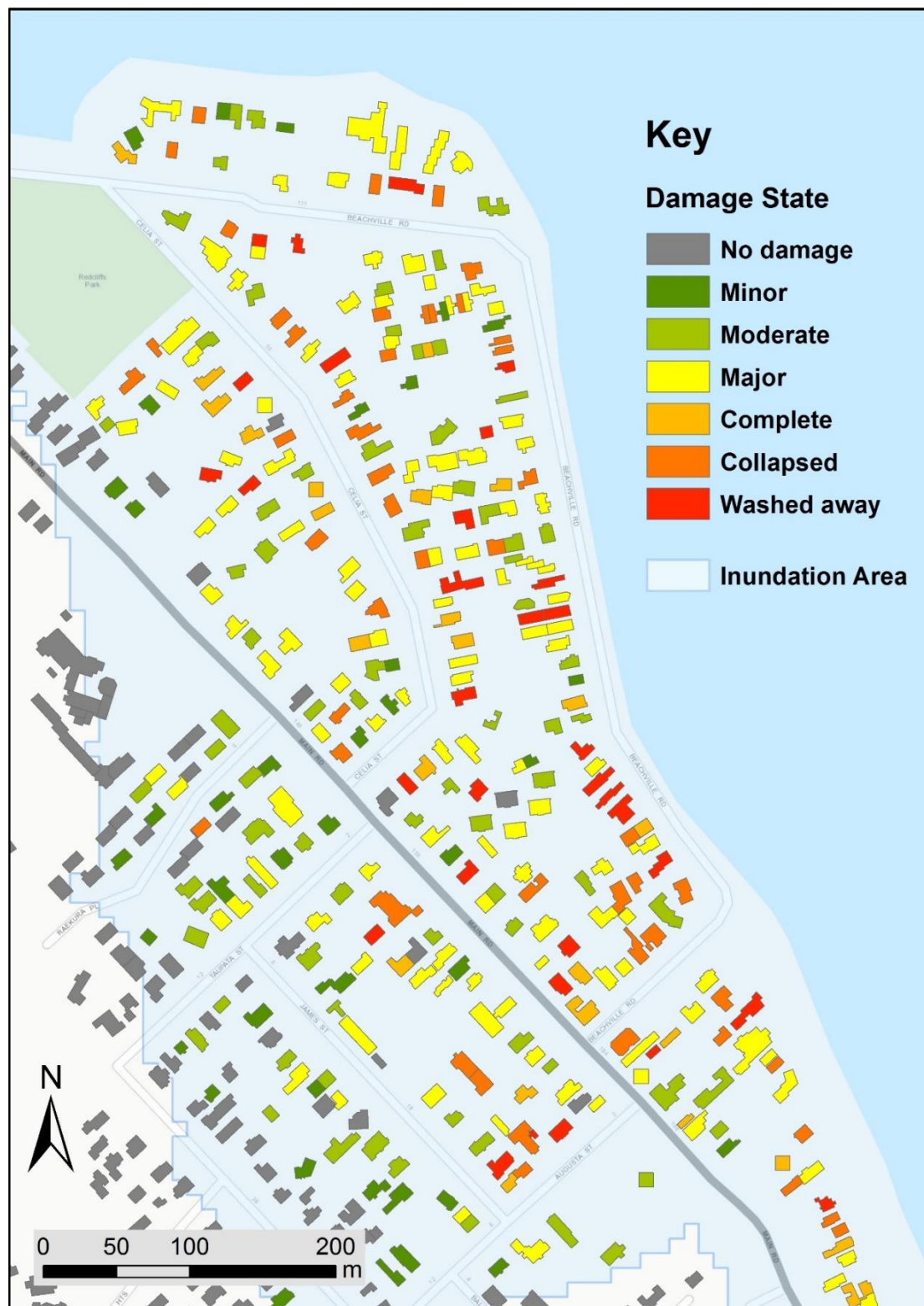


Figure B.2: Example map of Redcliffs showing the damage state distribution of a single run (#3) of the impact assessment modelling for the Okada40 scenario.

Appendix C: Polygons of access and utility disruption

Figures C.1 – C.11 show the polygons of disruption to access, power, water and wastewater used for the spatial and temporal modelling of residential building habitability (see page 87). Note that although some of the polygons extend into areas that may not be disrupted during the Okada40 tsunami scenario, only the buildings within the inundation zone and areas completely surrounded by inundation for the suburbs of New Brighton, South Brighton and Southshore are considered for the residential habitability and human displacement modelling. Some of the polygons extend beyond the study area for ease of creation using ArcMap.

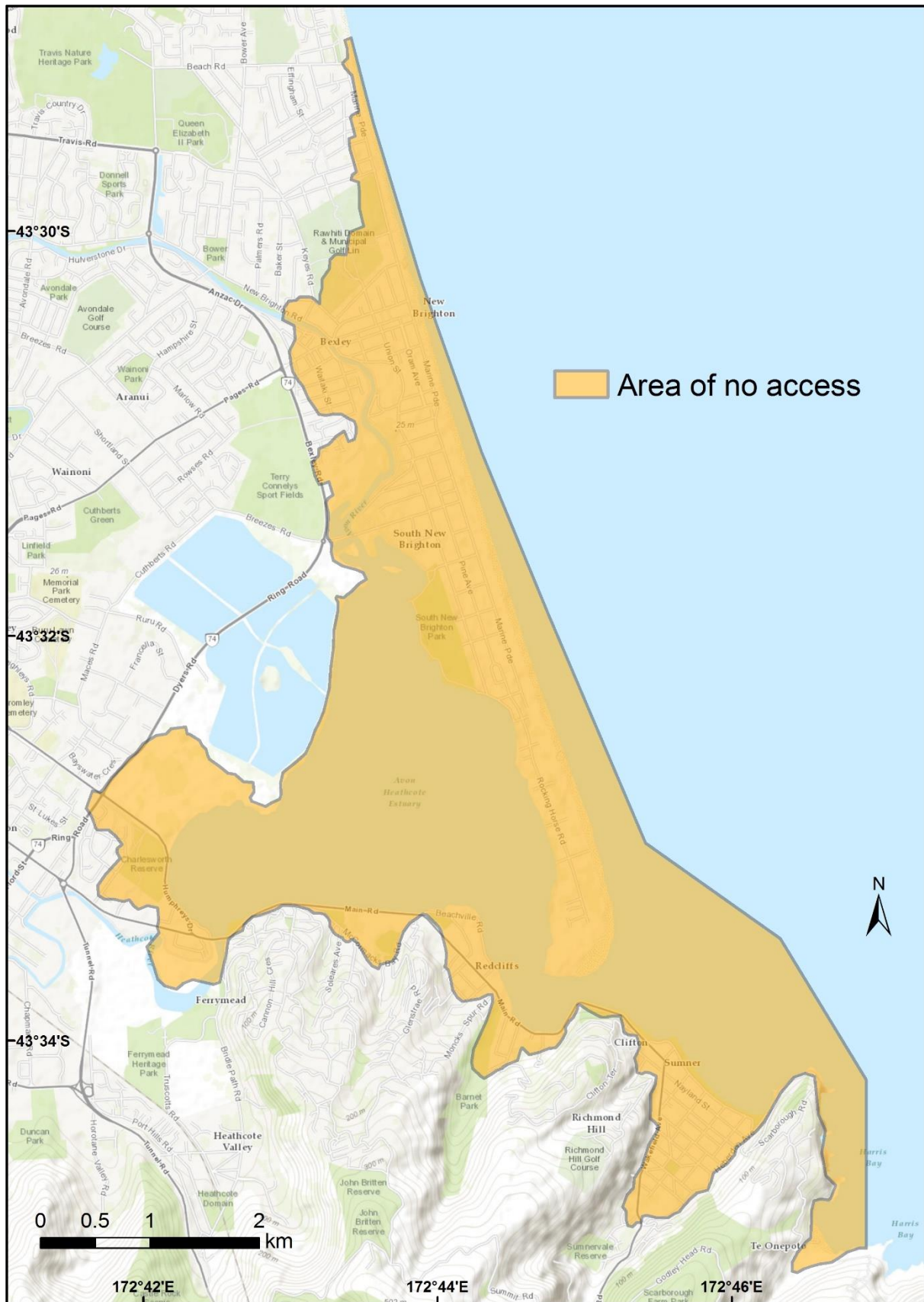


Figure C.1: Polygon showing area of no access for Day 1 following the tsunami wave arrival (Okada40).

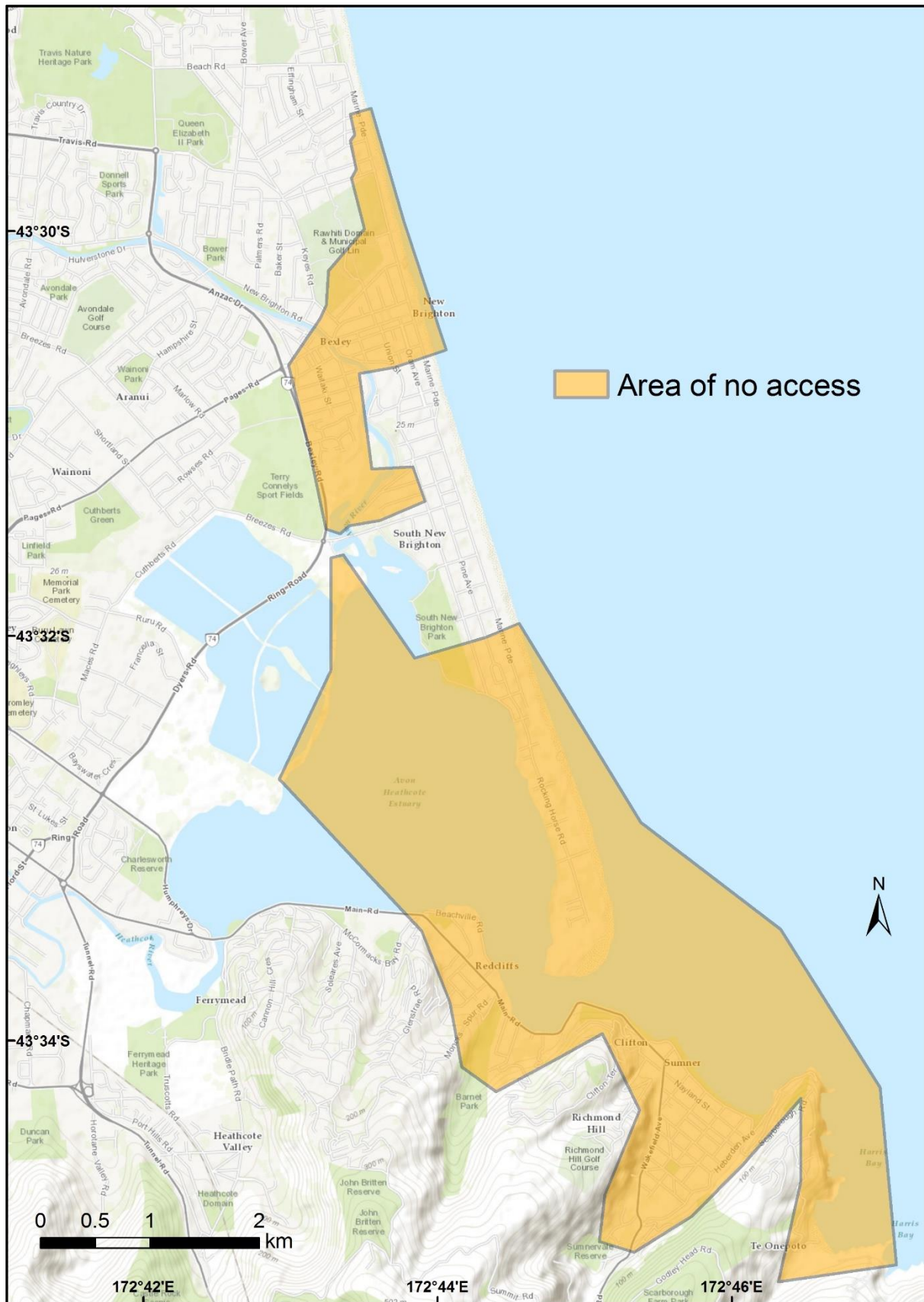


Figure C.2: Polygon showing area of no access for Days 2 - 3 following the tsunami wave arrival (Okada40).

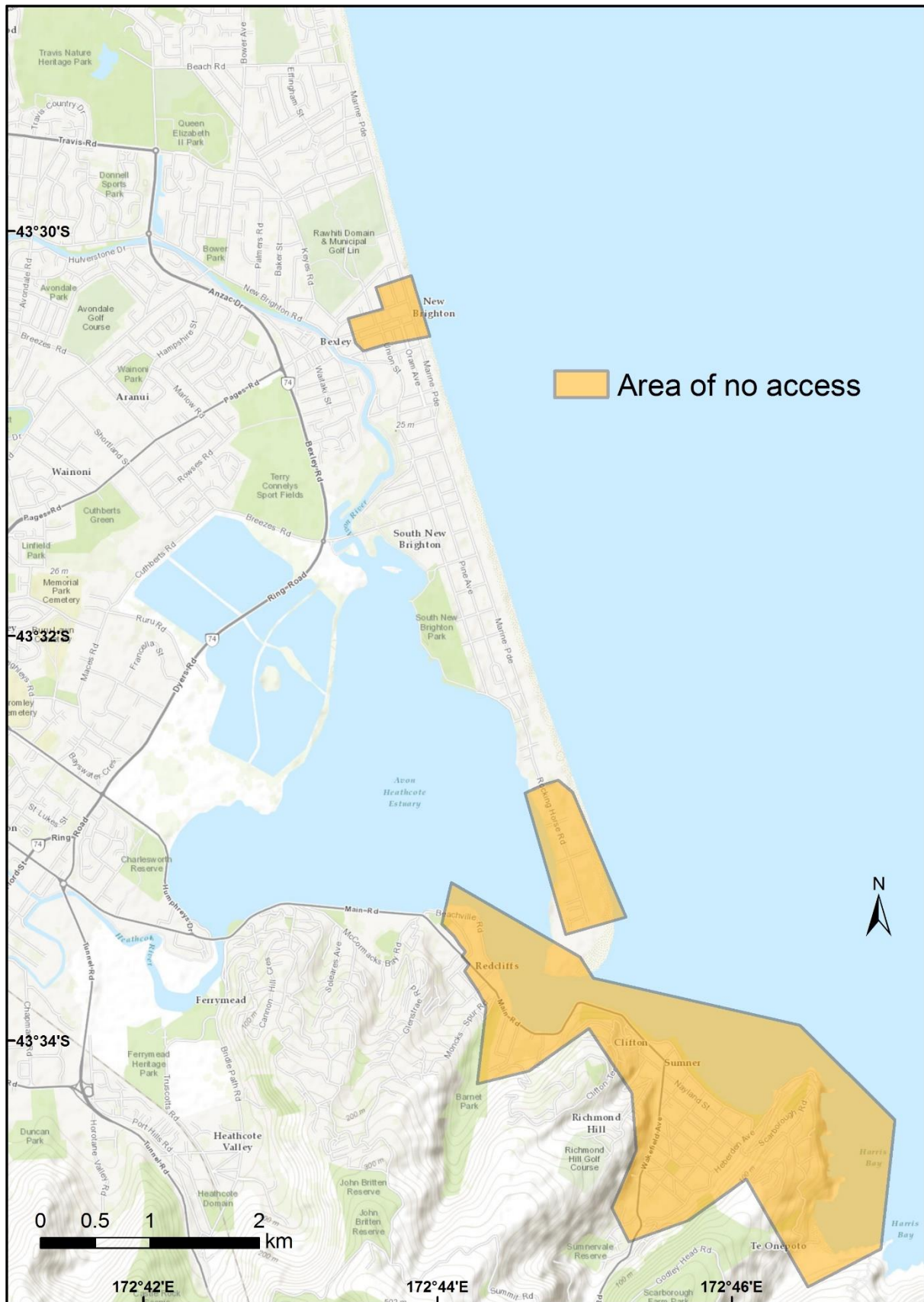


Figure C.3: Polygon showing area of no access for Day 4 following the tsunami wave arrival (Okada40).

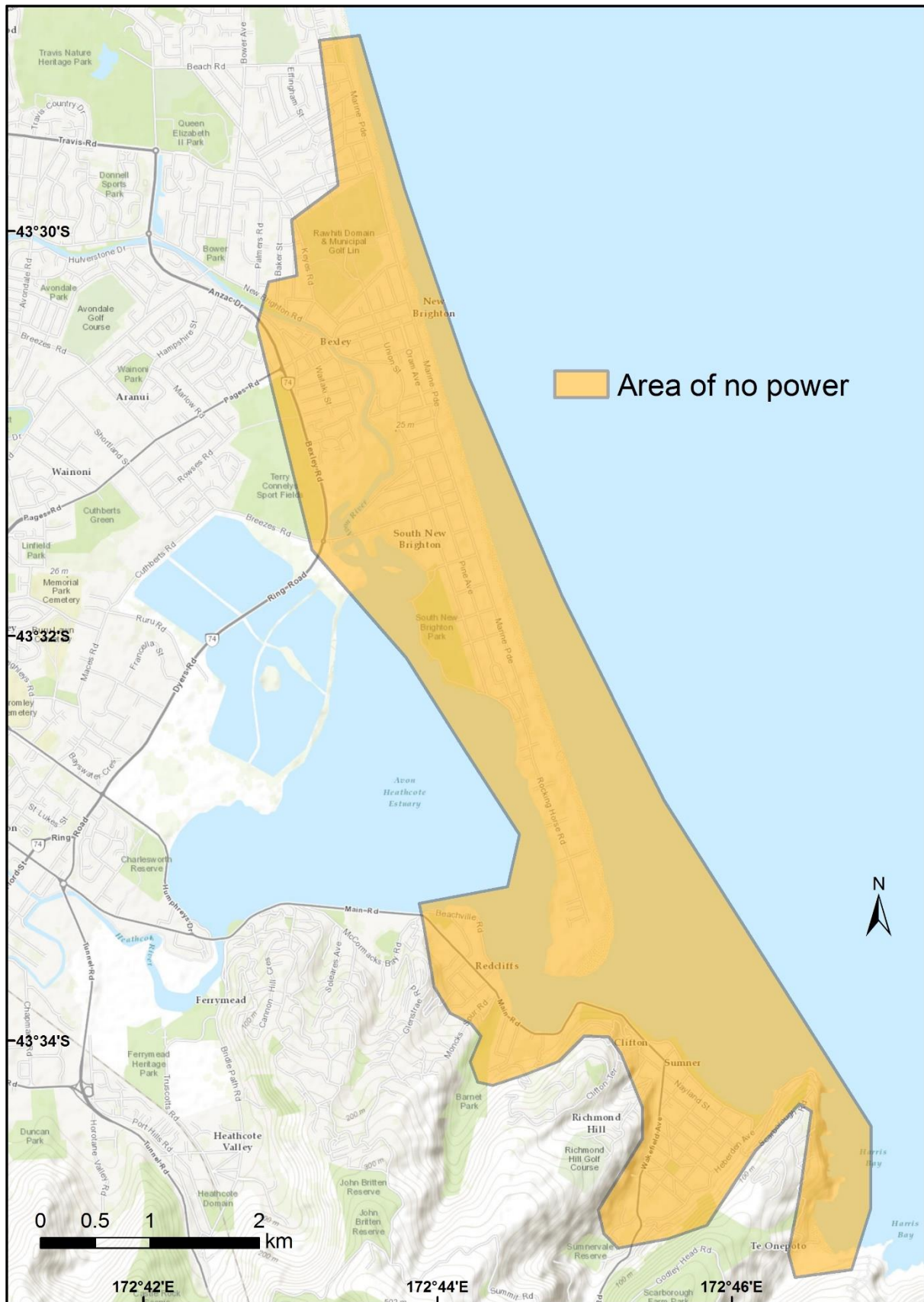


Figure C.4: Polygon showing area of no power for Days 1 - 4 following the tsunami wave arrival (Okada40).

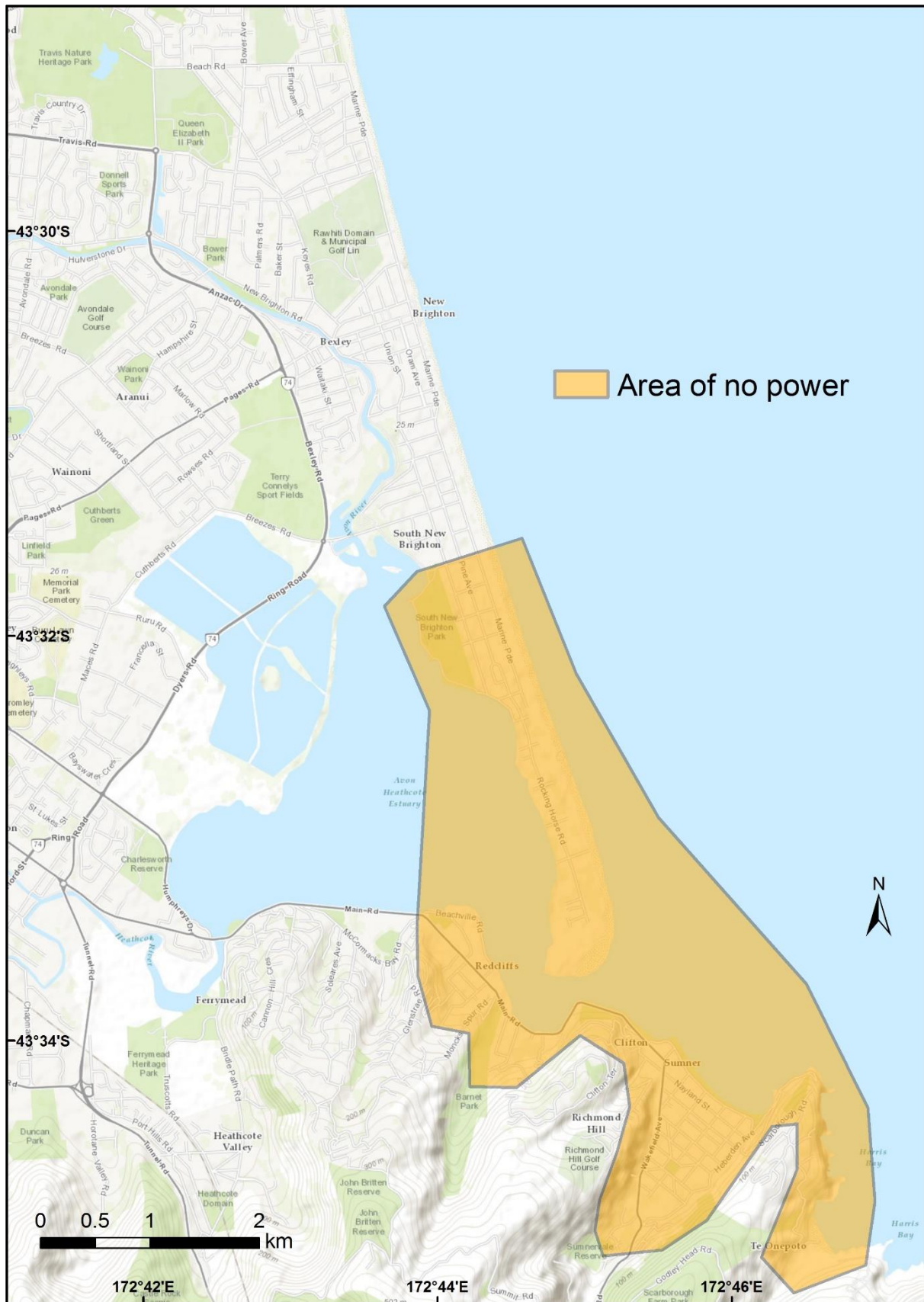


Figure C.5: Polygon showing area of no power for Days 5 – 6 following the tsunami wave arrival (Okada40).

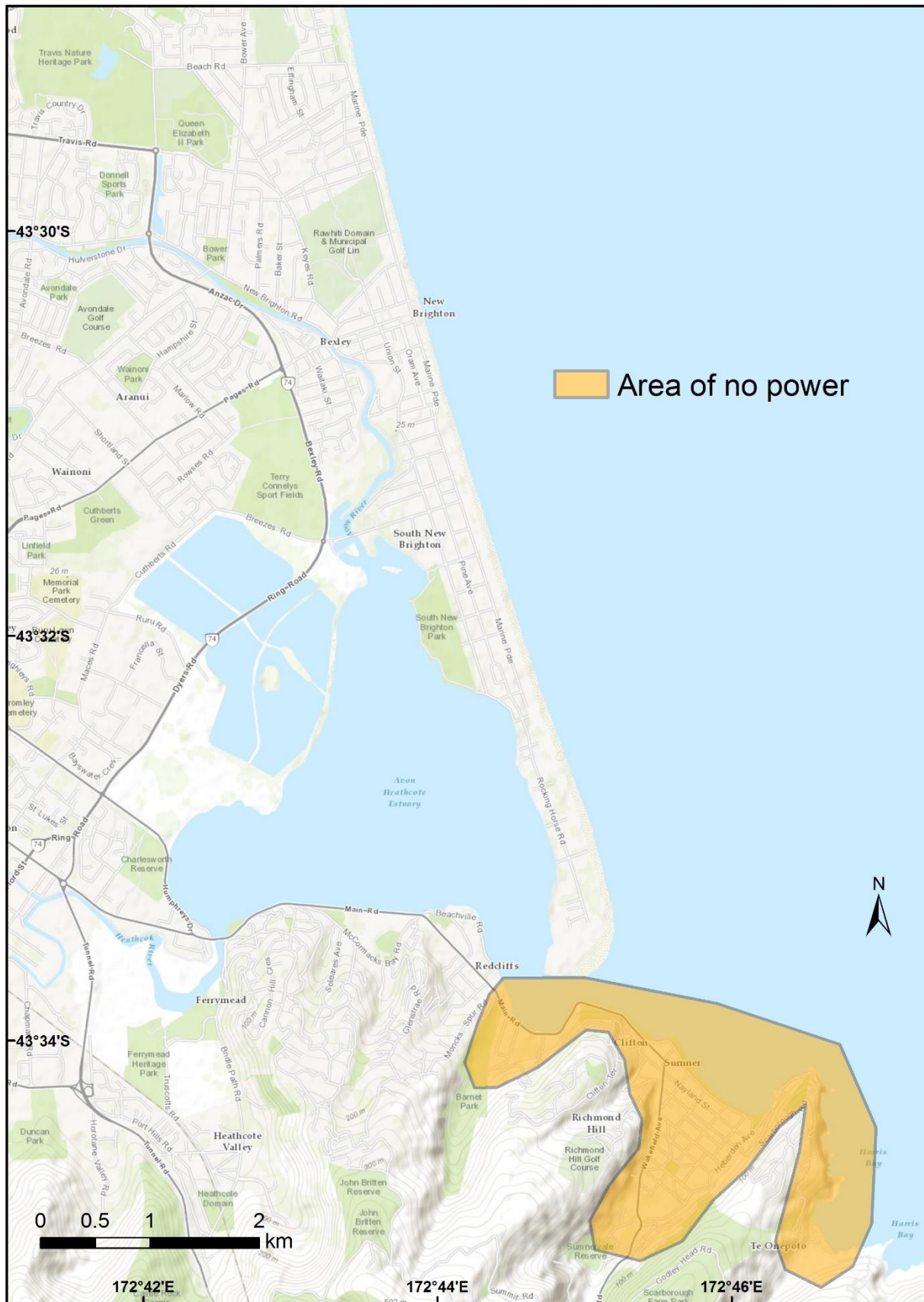


Figure C.6: Polygon showing area of no power for Day 7 onwards following the tsunami wave arrival (Okada40).

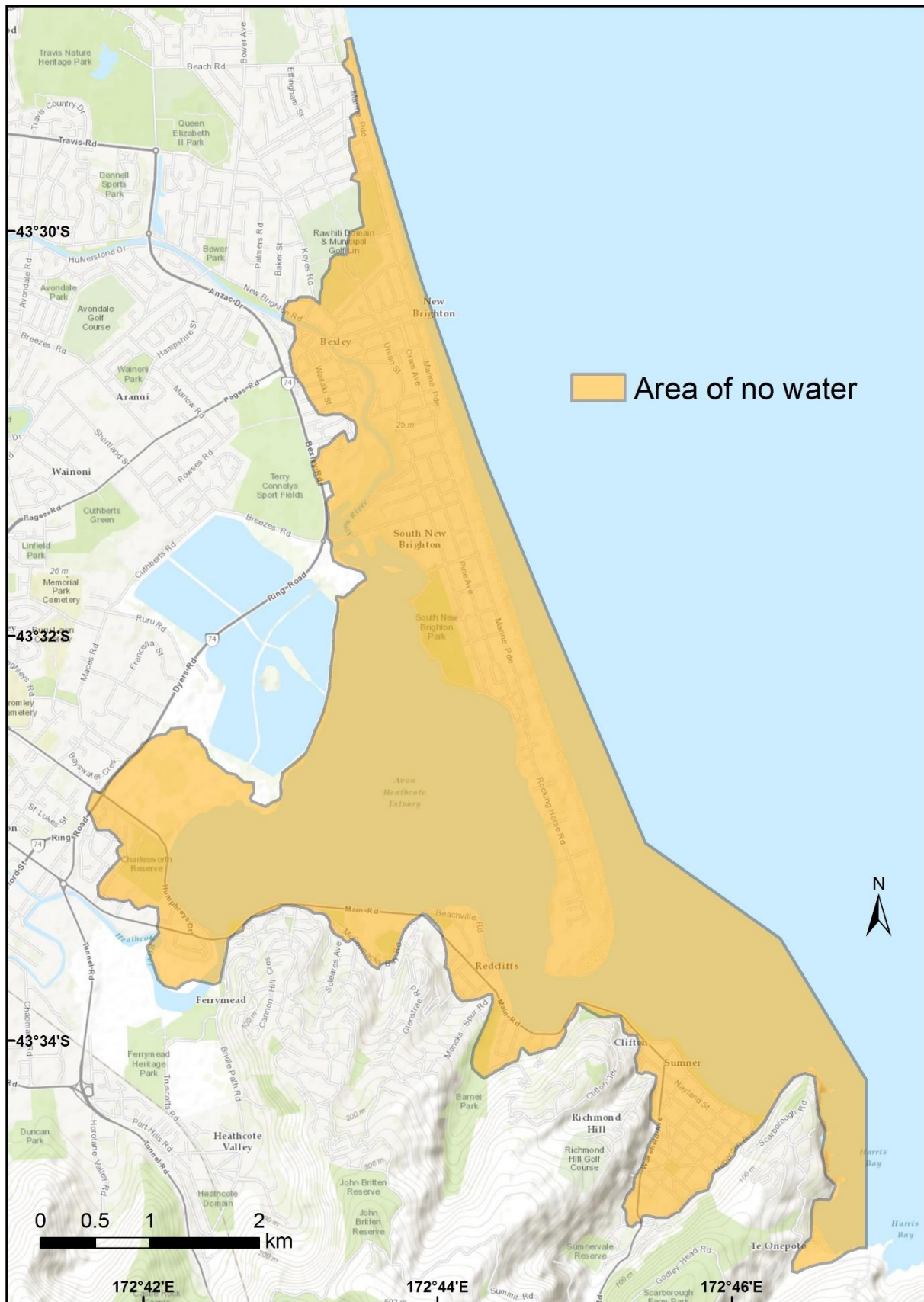


Figure C.7: Polygon showing area of no water for Days 1 - 4 following the tsunami wave arrival (Okada40).

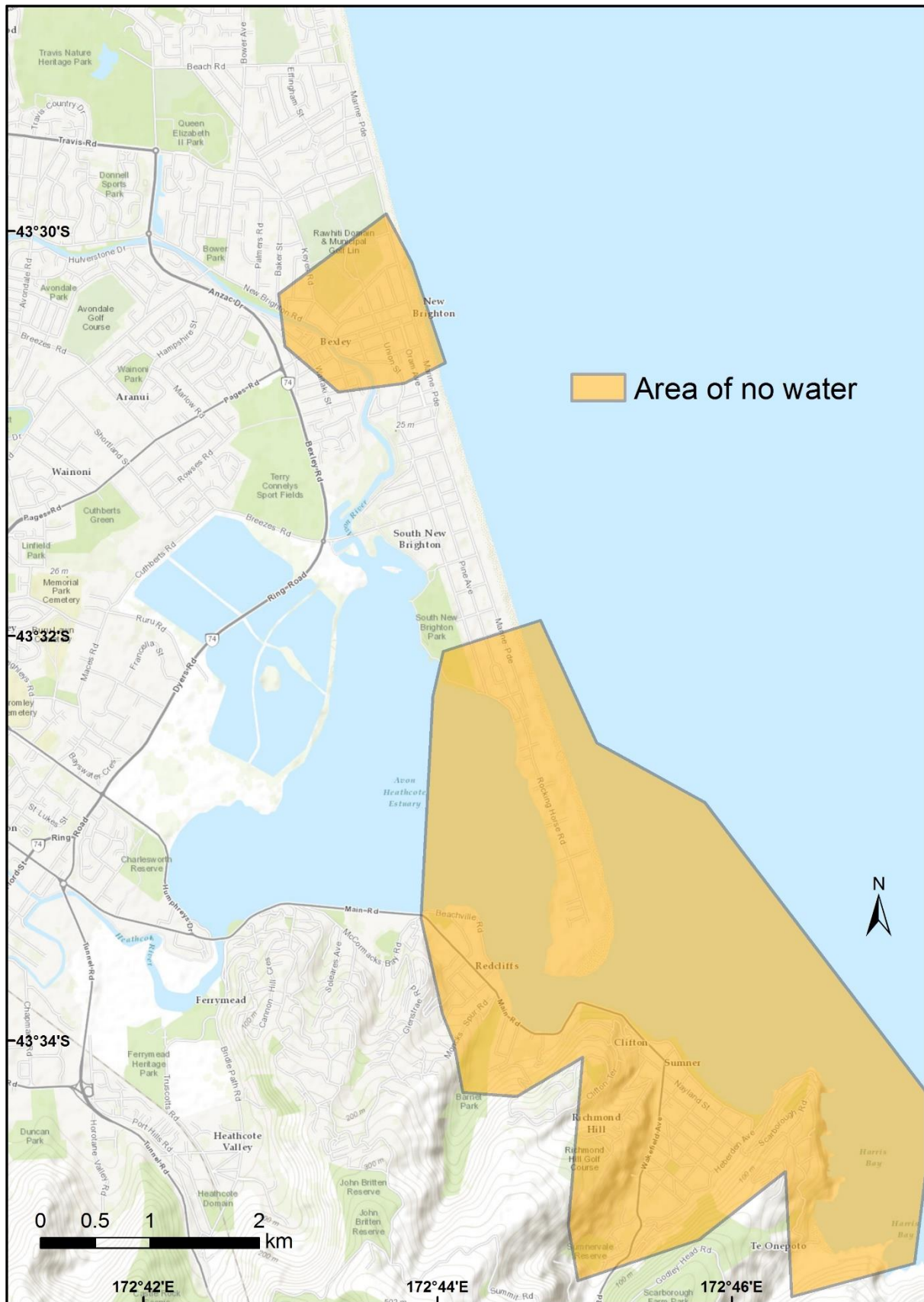


Figure C.8: Polygon showing area of no water for Day 5 onwards following the tsunami wave arrival (Okada40).

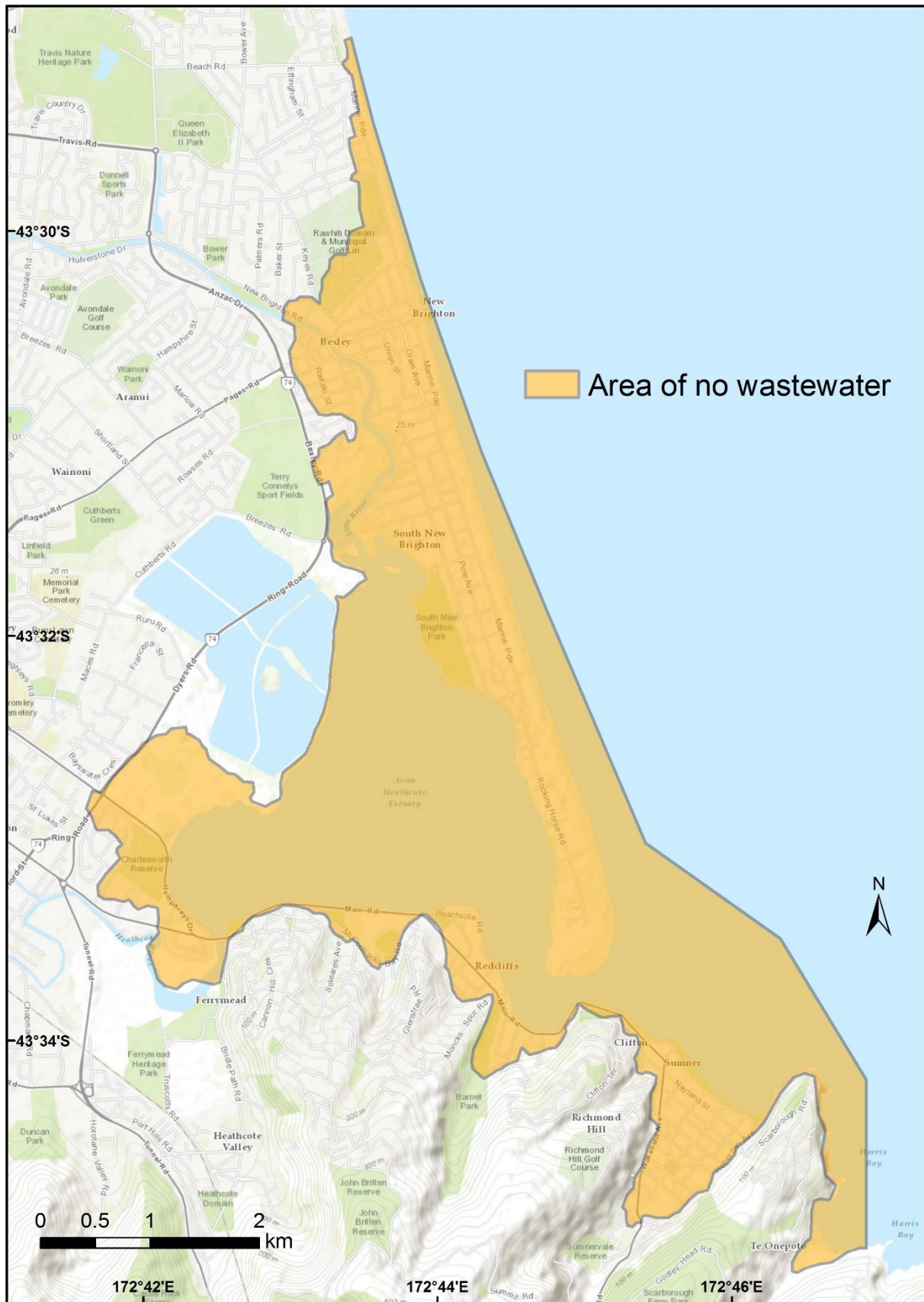


Figure C.9: Polygon showing area of no wastewater for Days 1 - 2 following the tsunami wave arrival (Okada40).

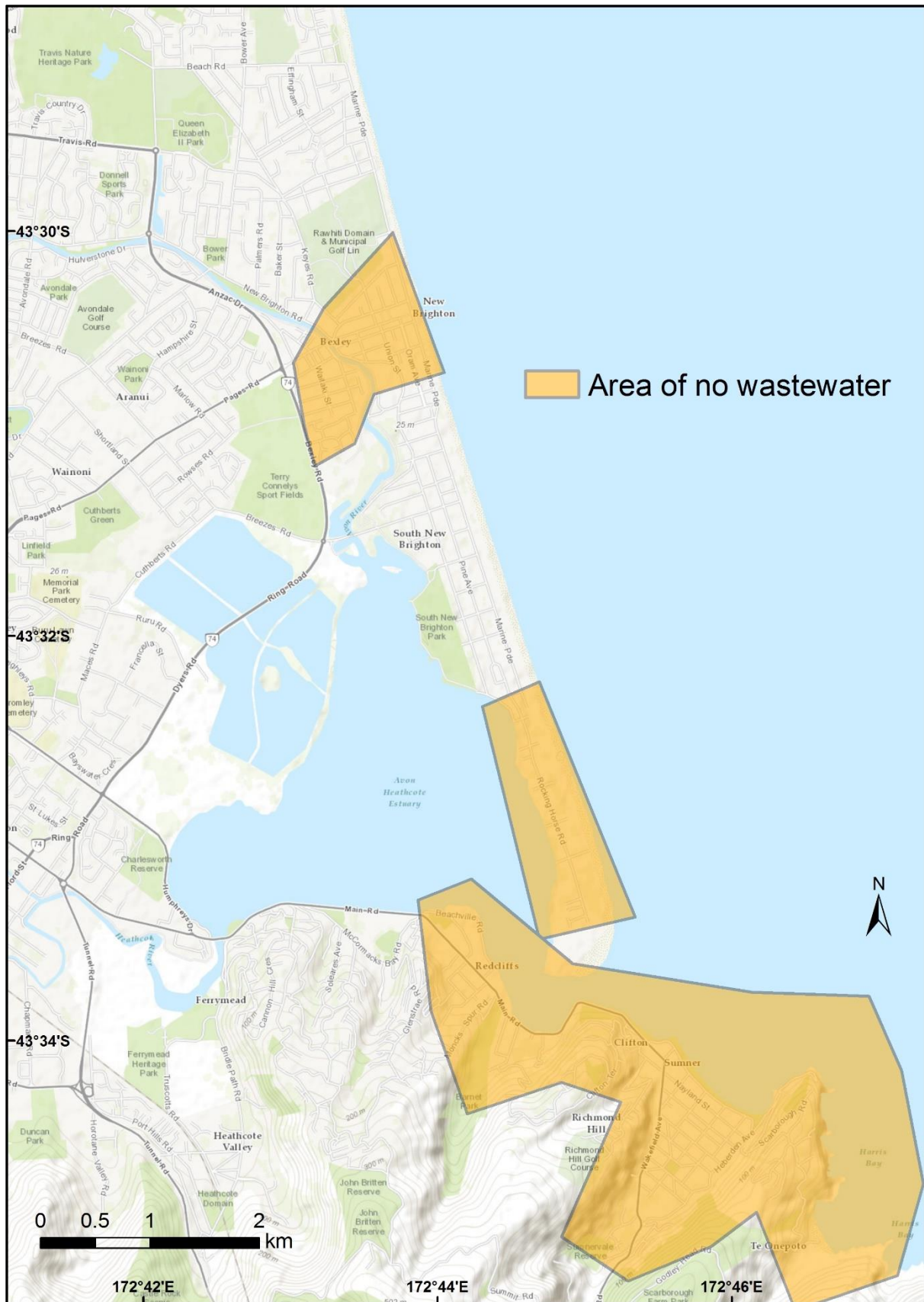


Figure C.10: Polygon showing area of no wastewater for Days 3 – 5 following the tsunami wave arrival (Okada40).

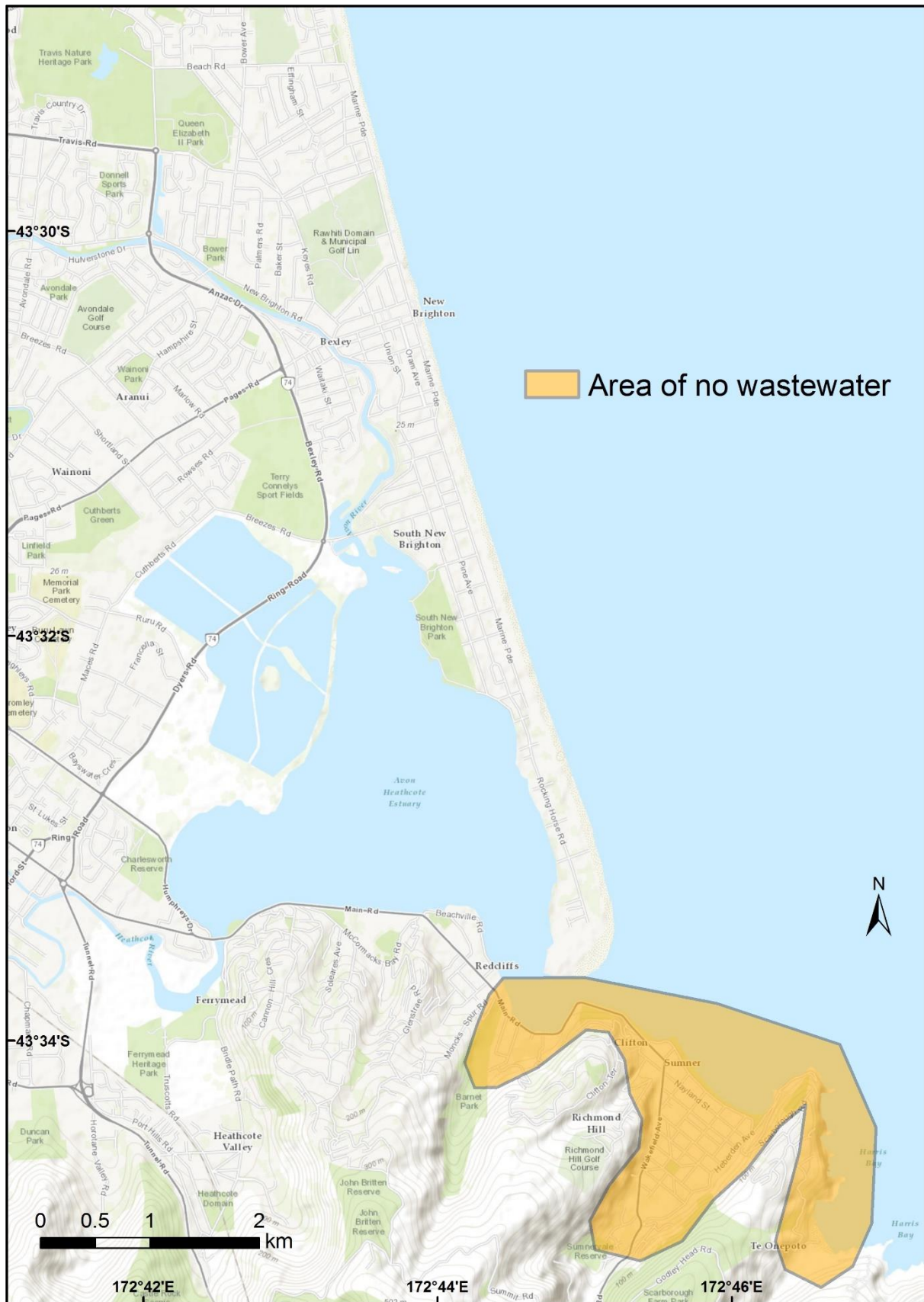


Figure C.11: Polygon showing area of no wastewater for Day 6 onwards following the tsunami wave arrival (Okada40).

Appendix D: Interview questions and Human Ethics approval

Interview questions

1. Briefly, what is your experience with natural hazards?
2. Following a tsunami that affects an urban area, in your opinion what would be the main factors that influence whether evacuated residents will return to their homes?
3. What are the main factors that determine whether a building is habitable?
4. On a scale of 0 – 5, 0 being “not at all important” and 5 being “essential”, how important would you rate each of the main residential utilities (power, water, wastewater) in determining whether a building is habitable?
5. If an evacuated resident is considering whether to return, how important would the normal functioning of their local community be to their decision?
6. Have you been to a location affected by a tsunami? If yes:
 - a. Which tsunami event?
 - b. Which specific locations did you visit?
 - c. How long after the initial event did you arrive?
 - d. Which organisation were you working for, and what was your role?
7. Have you experienced the aftermath of a significant natural event requiring evacuation? If yes:
 - a. How long was it before residents returned to their homes?
 - b. Do you think people relied more on official guidance or their own intuition and experience when deciding whether to return?
 - c. How influential were local government or official instructions to people’s actions after the event?
8. Do you have experience with the aftermath of a flooding event which affected buildings? If yes, how long do you think it generally takes before a building is habitable, after the point that water recedes?
9. Is there anything else you would like to add that might assist in an estimation of human displacement following a tsunami, or other natural event?



HUMAN ETHICS COMMITTEE

Secretary, Lynda Griffioen
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2015/75/LR

2 September 2015

Finn Scheele
Department of Geological Sciences
UNIVERSITY OF CANTERBURY

Dear Finn

Thank you for forwarding your Human Ethics Committee Low Risk application for your research proposal "Impact assessment of a far-field tsunami scenario for building habitability in Christchurch, New Zealand".

I am pleased to advise that the application has been reviewed and approved.

With best wishes for your project.

Yours sincerely

A handwritten signature in black ink, appearing to read 'L MacDonald'.

Lindsey MacDonald
Chair, Human Ethics Committee